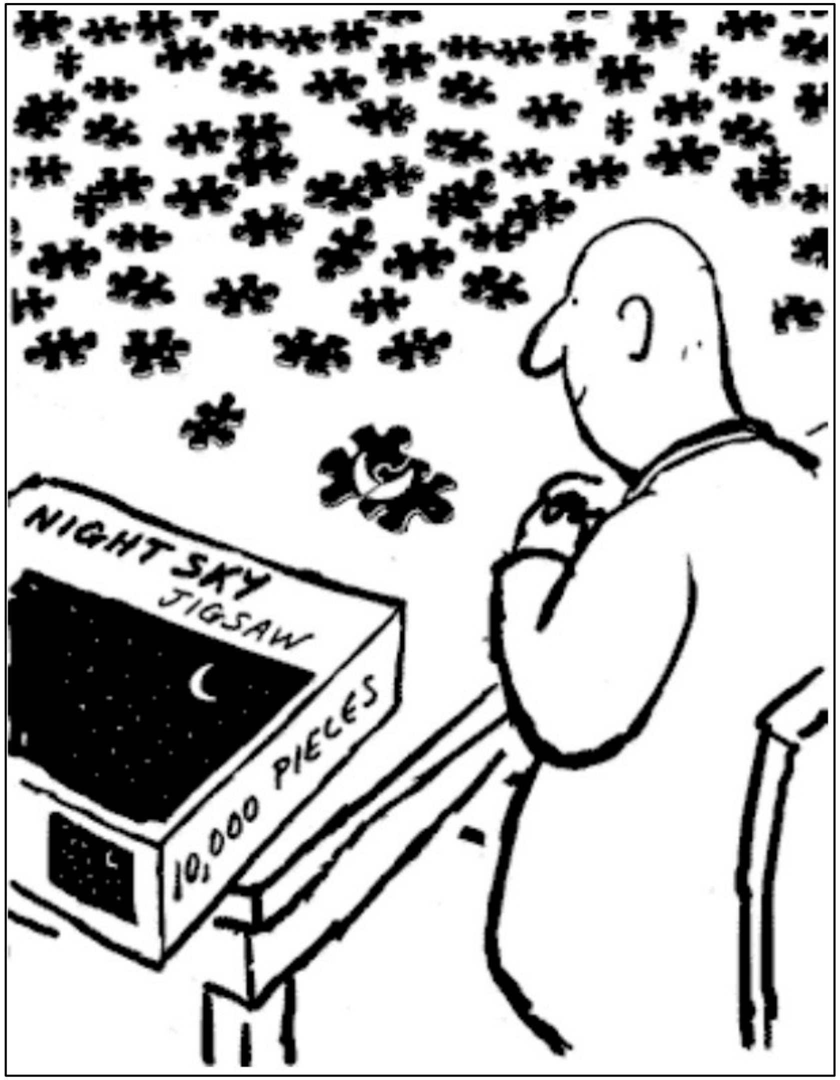
Cosmic Microwave Background

Alexander Knebe (*Universidad Autonoma de Madrid*)



- discovery
- origin
- CMB fluctuations
  - primary (created during inflation)
  - secondary (created after photon decoupling)

- **discovery**
- origin
- CMB fluctuations
  - primary (created during inflation)
  - secondary (created after photon decoupling)

- photon-to-baryon ratio (frozen in at BBNS)

$$\eta = \frac{n_b}{n_\gamma} = 10^{-10}\eta_{10} = 10^{-10} \cdot 274\Omega_b h^2$$

- photon-to-baryon ratio (frozen in at BBNS)

$$\eta = \frac{n_b}{n_\gamma} = 10^{-10}\eta_{10} = 10^{-10} \cdot 274\Omega_b h^2$$

=> there are lots of photons in the Universe!

- photon-to-baryon ratio (frozen in at BBNS)

$$\eta = \frac{n_b}{n_\gamma} = 10^{-10}\eta_{10} = 10^{-10} \cdot 274\Omega_b h^2$$

=> there are lots of photons in the Universe!

- barotropic fluids $p = \omega \rho c^2$:

  - **radiation** $\boldsymbol{w = 1/3 \quad \Rightarrow \quad T \propto R^{-1}}$
  - matter $w = 0 \quad \Rightarrow \quad T \propto R^{-2}$

=> and even though their temperature dropped they should still be observable today!?

- photons in thermal equilibrium

$$u(\nu)d\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/k_BT}-1}d\nu$$

(Planck curve, spectral energy density ρ_{rad})

- adiabatically expanding Universe (see FRW lecture)

$$T \propto R^{-1}$$

$$p \propto R^{-1} \Leftrightarrow \nu \propto R^{-1}$$

- photons in thermal equilibrium

$$u(\nu)d\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/k_BT}-1}d\nu$$

(Planck curve, spectral energy density ρ_{rad})

- adiabatically expanding Universe (see FRW lecture)

$$T \propto R^{-1}$$

$$p \propto R^{-1} \Leftrightarrow \nu \propto R^{-1}$$

- adiabatically expanding photons **(exercise)**

$$u(\tilde{\nu})d\tilde{\nu} = R^{-4}\frac{8\pi h\tilde{\nu}^3}{c^3}\frac{1}{e^{h\tilde{\nu}/k_B\tilde{T}}-1}d\tilde{\nu}$$

(Planck curve with $\tilde{T} = T/R$)

- photons in thermal equilibrium

$$u(\nu)d\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/k_BT}-1}d\nu$$

(Planck curve, spectral energy density $\rho_{\rm rad}$)

- adiabatically expanding Universe (see FRW lecture)

$$T \propto R^{-1}$$
$$p \propto R^{-1} \Leftrightarrow \nu \propto R^{-1}$$

- adiabatically expanding photons

$$u(\tilde{\nu})d\tilde{\nu} = \boxed{R^{-4}}\frac{8\pi h\tilde{\nu}^3}{c^3}\frac{1}{e^{h\tilde{\nu}/k_B\tilde{T}}-1}d\tilde{\nu}$$

(Planck curve with $\tilde{T} = T/R$)

(in agreement with $\rho_{rad} \propto R^{-4}$ as seen in Thermal History lecture)

- photons in thermal equilibrium

$$u(\nu)d\nu = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/k_BT}-1}d\nu$$

(Planck curve, spectral energy density $\rho_{\rm rad}$)

- adiabatically expanding Universe (see FRW lecture)

black-body radiation in an expanding Universe cools down,
but remains thermal (Tolman 1934).

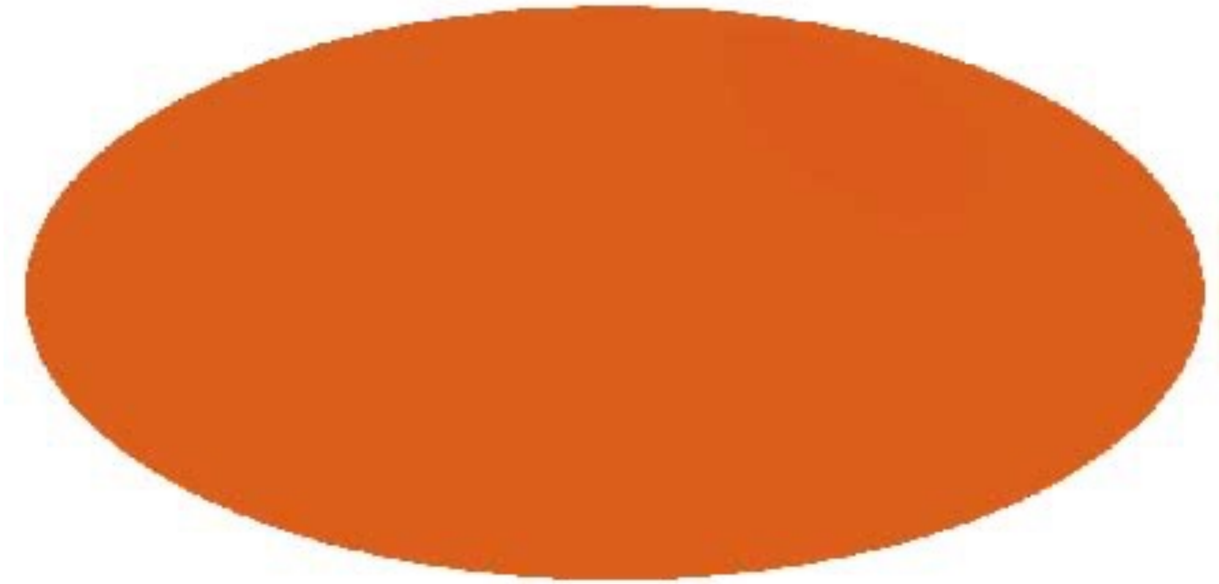
- adiabatically expanding photons

$$u(\tilde{\nu})d\tilde{\nu} = R^{-4}\frac{8\pi h\tilde{\nu}^3}{c^3}\frac{1}{e^{h\tilde{\nu}/k_B\tilde{T}}-1}d\tilde{\nu}$$

(Planck curve with $\tilde{T} = T/R$)

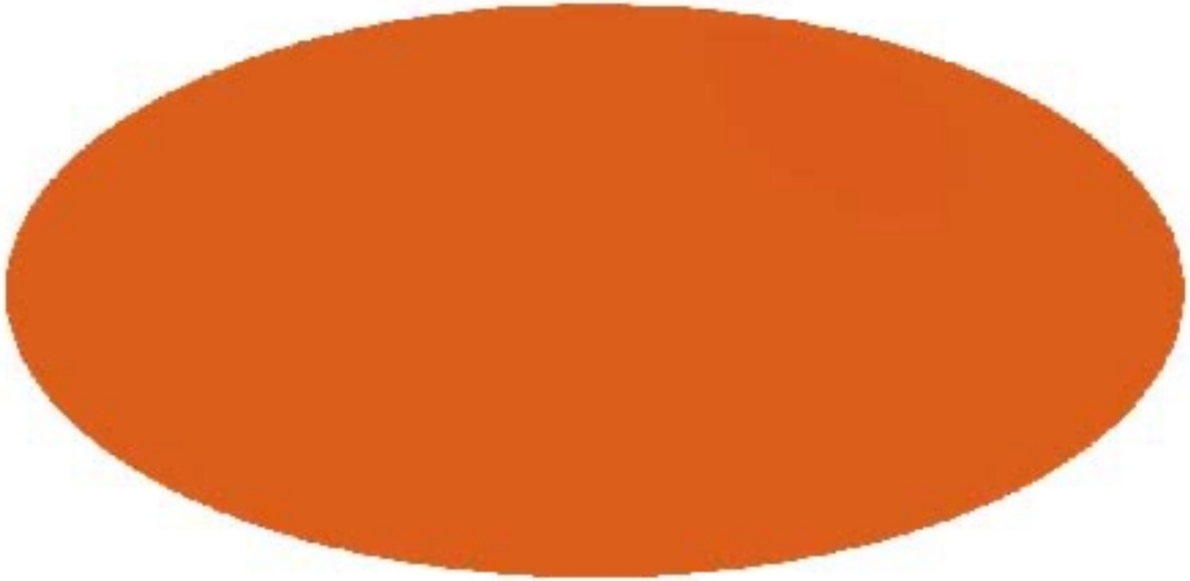
(in agreement with $\rho_{rad} \propto R^{-4}$ as seen in Thermal History lecture)

- predictions of isotropic cosmic background radiation



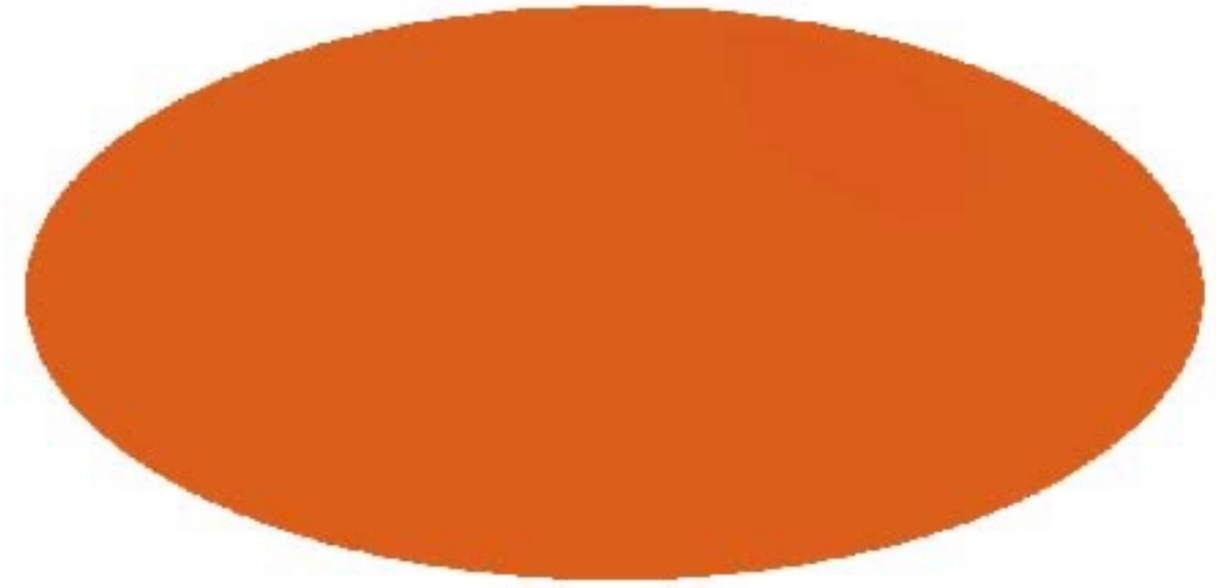
- 1946: George Gamow predicts $T \approx 50$K
- 1948: Ralph Alpher & Robert Herman predict $T \approx 5$K
- 1960: Robert Dicke re-estimates $T \approx 40$K
- 1964: A. Doroshkevich & Igor Novikov suggest to search for the CMB!

- predictions of isotropic cosmic background radiation



- 1946: George Gamow predicts $T \approx 50$K
- 1948: Ralph Alpher & Robert Herman predict $T \approx 5$K
- 1960: Robert Dicke re-estimates $T \approx 40$K
- 1964: A. Doroshkevich & Igor Novikov suggest to search for the CMB!
- 1965: discovered by Arno Penzias & Robert Wilson

- predictions of isotropic cosmic background radiation



- 1946: George Gamow predicts $T \approx 50$K
- 1948: Ralph Alpher & Robert Herman predict $T \approx 5$K
- 1960: Robert Dicke re-estimates $T \approx 40$K
- 1964: A. Doroshkevich & Igor Novikov suggest to search for the CMB!
- 1965: discovered by Arno Penzias & Robert Wilson ?

- discovered 1957 by Emile Le Roux
  - PhD student at Nancay Radio Observatory (France)
  - found near-isotropic background of 3K at λ=33cm

Reproduction of page 50 of (Leroux's thesis).

En résumé, on a trois équations donnant T_c :

$$v_o = 0 \qquad 137 = 138 - 0,485\ T_c \longrightarrow T_c = 2^\circ K$$

$$(25) \qquad v_o = 5 \qquad 50 = 51,3 - 0,485\ T_c \longrightarrow T_c = 2,7^\circ K$$

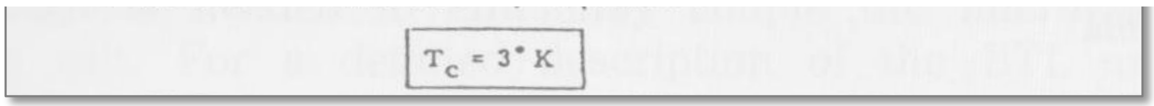
$$v_o = -3 \qquad 215 = 218 - 0,77\ T_c \longrightarrow T_c = 3,9^\circ K.$$

En fait, on devrait déduire, de plusieurs équations de ce genre, les coefficients $1/k$, ρ, ρ', ρ'' et T_c. Mais la bonne cohérence des valeurs obtenues pour T_c montre que les valeurs prises pour ces coefficients sont correctes avec une bonne approximation. Si on diminuait le coefficient $1/k$ on obtiendrait des valeurs négatives pour T_c, quelles que soient les valeurs prises pour ρ' et ρ'' qui interviennent de façon différente dans les 3 équations précédentes, le coefficient ρ' intervenant notamment de façon opposée dans les deux dernières équations. De même, une augmentation de $1/k$ de quelques pour cent donnerait des valeurs de T_c incohérentes. Enfin, un coefficient de réflection du sol non nul donnerait $T_c < 0$.

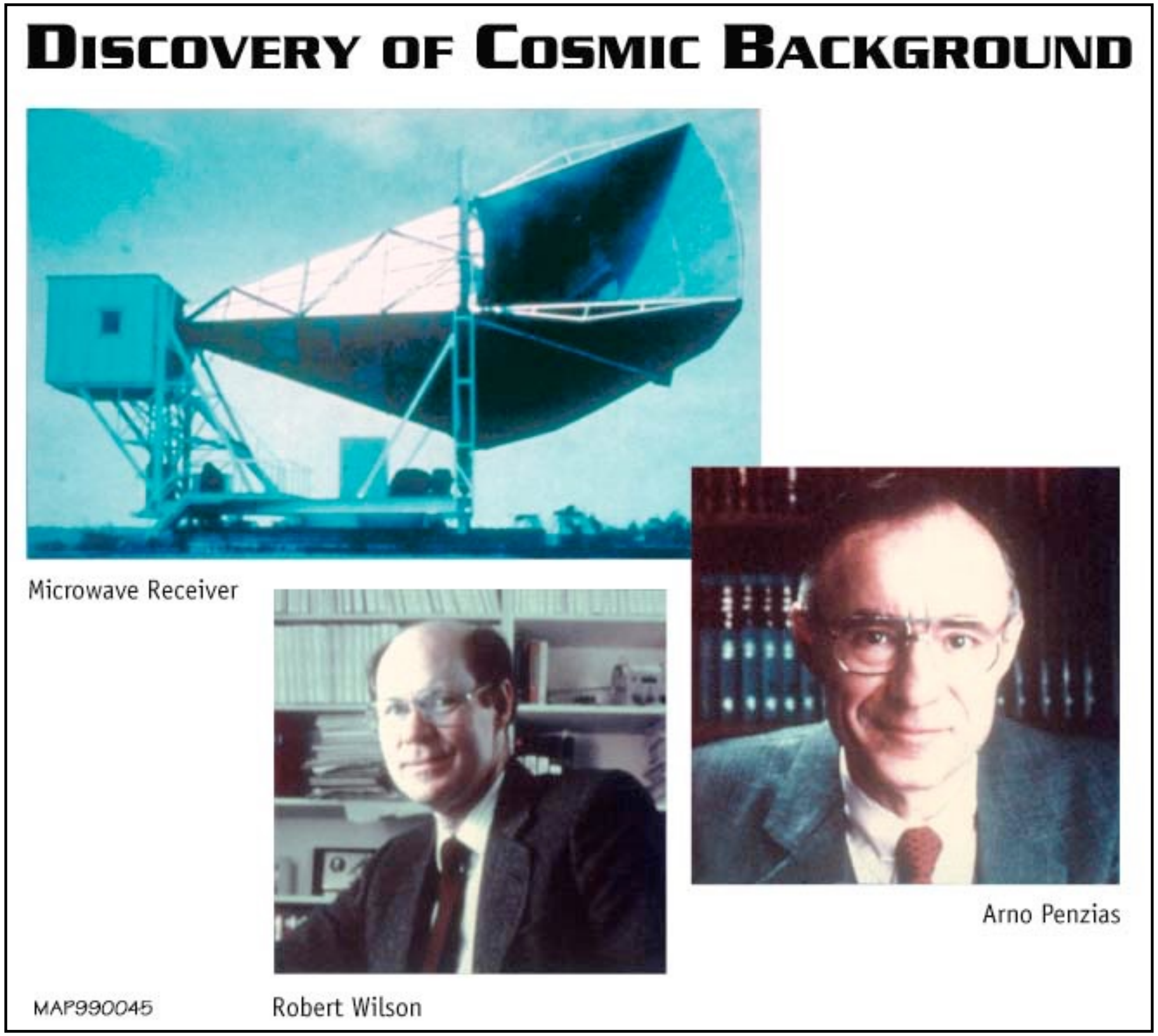
Il est difficile de déterminer l'erreur sur cette valeur de T_c, basée sur la cohérence de différentes mesures. Nous pensons que l'erreur absolue doit être de l'ordre de 2° K, en prenant :

$$\boxed{T_c = 3^\circ K}$$

- discovered 1957 by Emile Le Roux
    - PhD student at Nancay Radio Observatory (France)
    - found near-isotropic background of 3K at λ=33cm
    - removed from article following suggestion of her supervisor…


$T_c = 3° K$

- (re-)discovered 1965 by Penzias & Wilson
- Nobel prize in 1978



- not very spectacularly announced…

high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm^3 is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

REFERENCES

Alpher, R. A , Bethe, H. A , and Gamow, G 1948, *Phys. Rev.*, **73**, 803
Alpher, R A., Follin, J W., and Herman, R. C. 1953, *Phys. Rev* , **92**, 1347.
Bondi, H , and Gold, T. 1948, *M N.*, **108**, 252.
Brans, C , and Dicke, R. H 1961, *Phys. Rev.*, **124**, 925.
Dicke, R. H. 1962, *Phys. Rev.*, **125**, 2163.
Dicke, R. H , Beringer, R., Kyhl, R L , and Vane, A B. 1946, *Phys. Rev.*, **70**, 340
Einstein, A , 1950, *The Meaning of Relativity* (3d ed.; Princeton, N.J.: Princeton University Press), p. 107.
Hoyle, F. 1948, *M N* , **108**, 372.
Hoyle, F , and Tayler, R J 1964, *Nature*, **203**, 1108
Liftshitz, E M., and Khalatnikov, I. M 1963, *Adv. in Phys* , **12**, 185.
Oort, J H 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf [Brussels: Éditions Stoops]), p. 163.
Peebles, P J. E. 1965, *Phys. Rev.* (in press).
Penzias, A. A., and Wilson, R. W. 1965, private communication.
Wheeler, J. A , 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 112.
——— 1964, in *Relativity, Groups and Topology*, ed C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

© American Astronomical Society • Provided by the NASA Astrophysics Data System

- interpretation in same ApJ issue…

high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm^3 is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

REFERENCES

Alpher, R. A , Bethe, H. A , and Gamow, G 1948, *Phys. Rev.*, **73**, 803
Alpher, R A., Follin, J W., and Herman, R. C. 1953, *Phys. Rev* , **92**, 1347.
Bondi, H , and Gold, T. 1948, *M N.*, **108**, 252.
Brans, C , and Dicke, R. H 1961, *Phys. Rev.*, **124**, 925.
Dicke, R. H. 1962, *Phys. Rev.*, **125**, 2163.
Dicke, R. H , Beringer, R., Kyhl, R L , and Vane, A B. 1946, *Phys. Rev.*, **70**, 340
Einstein, A , 1950, *The Meaning of Relativity* (3d ed.; Princeton, N.J.: Princeton University Press), p. 107.
Hoyle, F. 1948, *M N* , **108**, 372.
Hoyle, F , and Tayler, R J 1964, *Nature*, **203**, 1108
Liftshitz, E M., and Khalatnikov, I. M 1963, *Adv. in Phys* , **12**, 185.
Oort, J H 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf [Brussels: Éditions Stoops]), p. 163.
Peebles, P J. E. 1965, *Phys. Rev.* (in press).
Penzias, A. A., and Wilson, R. W. 1965, private communication.
Wheeler, J. A , 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 112.
——— 1964, in *Relativity, Groups and Topology*, ed C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

© American Astronomical Society • Provided by the NASA Astrophysics Data System

- interpretation in same ApJ issue…

…though dates back to ideas by Alpher, Bethe & Gamov in 1948

high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm^3 is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

REFERENCES

Alpher, R. A , Bethe, H. A , and Gamow, G 1948, *Phys. Rev.*, **73**, 803
Alpher, R A., Follin, J W., and Herman, R. C. 1953, *Phys. Rev* , **92**, 1347.
Bondi, H , and Gold, T. 1948, *M N* , **108**, 252.
Brans, C , and Dicke, R. H 1961, *Phys. Rev.*, **124**, 925.
Dicke, R. H. 1962, *Phys. Rev.*, **125**, 2163.
Dicke, R. H , Beringer, R., Kyhl, R L , and Vane, A B. 1946, *Phys. Rev.*, **70**, 340
Einstein, A , 1950, *The Meaning of Relativity* (3d ed.; Princeton, N.J.: Princeton University Press), p. 107.
Hoyle, F. 1948, *M N* , **108**, 372.
Hoyle, F , and Tayler, R J 1964, *Nature*, **203**, 1108
Liftshitz, E M., and Khalatnikov, I. M 1963, *Adv. in Phys* , **12**, 185.
Oort, J H 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf [Brussels: Éditions Stoops]), p. 163.
Peebles, P J. E. 1965, *Phys. Rev.* (in press).
Penzias, A. A., and Wilson, R. W. 1965, private communication.
Wheeler, J. A , 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 112.
——— 1964, in *Relativity, Groups and Topology*, ed C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

© American Astronomical Society • Provided by the NASA Astrophysics Data System

- interpretation in same ApJ issue…

…though dates back to ideas by Alpher, Bethe & Gamov in 1948:

Dicke, Peebles & Wilkinson were actually designing an experiment to search for the CMB…

…but eventually decided to publish jointly w/ Penzias & Wilson!*

No. 1, 1965 LETTERS TO THE EDITOR 419

high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm^3 is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

REFERENCES

Alpher, R. A , Bethe, H. A , and Gamow, G 1948, *Phys. Rev.*, **73**, 803
Alpher, R A., Follin, J W., and Herman, R. C. 1953, *Phys. Rev* , **92**, 1347.
Bondi, H , and Gold, T. 1948, *M N.*, **108**, 252.
Brans, C , and Dicke, R. H 1961, *Phys. Rev.*, **124**, 925.
Dicke, R. H. 1962, *Phys. Rev.*, **125**, 2163.
Dicke, R. H , Beringer, R., Kyhl, R L , and Vane, A B. 1946, *Phys. Rev.*, **70**, 340
Einstein, A , 1950, *The Meaning of Relativity* (3d ed.; Princeton, N.J.: Princeton University Press), p. 107.
Hoyle, F. 1948, *M N* , **108**, 372.
Hoyle, F , and Tayler, R J 1964, *Nature*, **203**, 1108
Liftshitz, E M., and Khalatnikov, I. M 1963, *Adv. in Phys* , **12**, 185.
Oort, J H 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf [Brussels: Éditions Stoops]), p. 163.
Peebles, P J. E. 1965, *Phys. Rev.* (in press).
Penzias, A. A., and Wilson, R. W. 1965, private communication.
Wheeler, J. A , 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 112.
——— 1964, in *Relativity, Groups and Topology*, ed C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

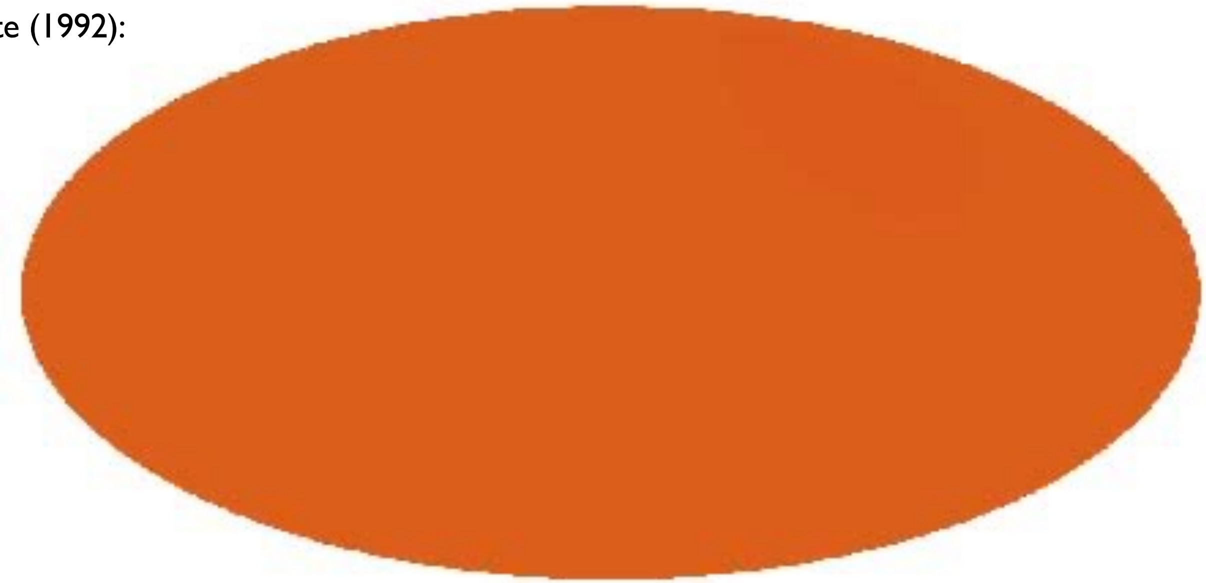
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

© American Astronomical Society • Provided by the NASA Astrophysics Data System

*but the Nobel prize was only awarded for the discovery, not for the interpretation…

- black body radiation?

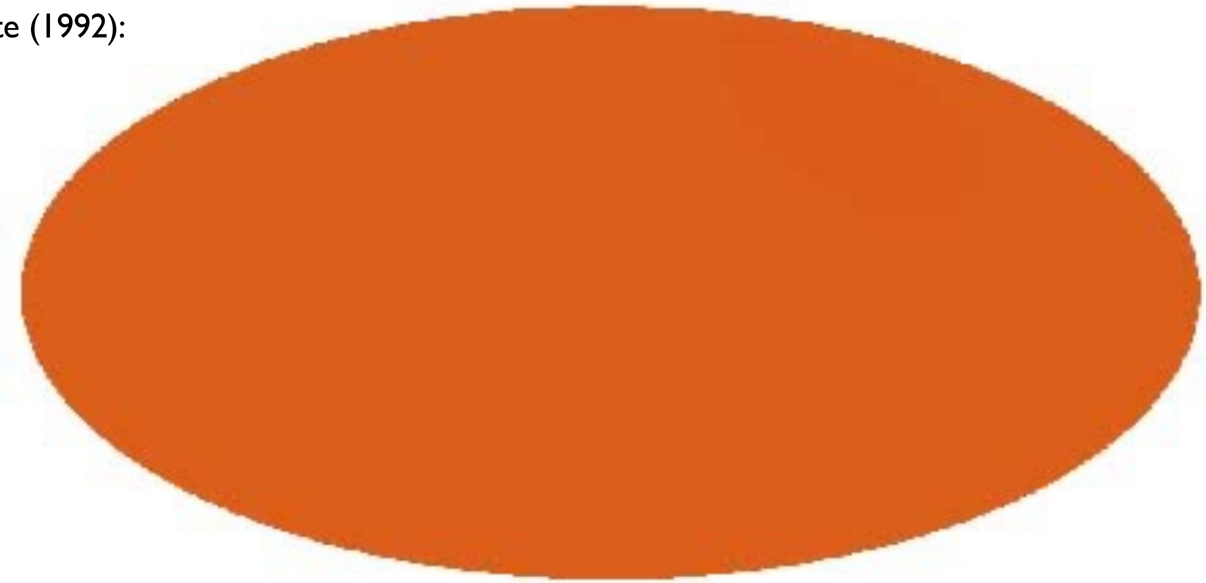
COBE satellite (1992):



T = 2.725K

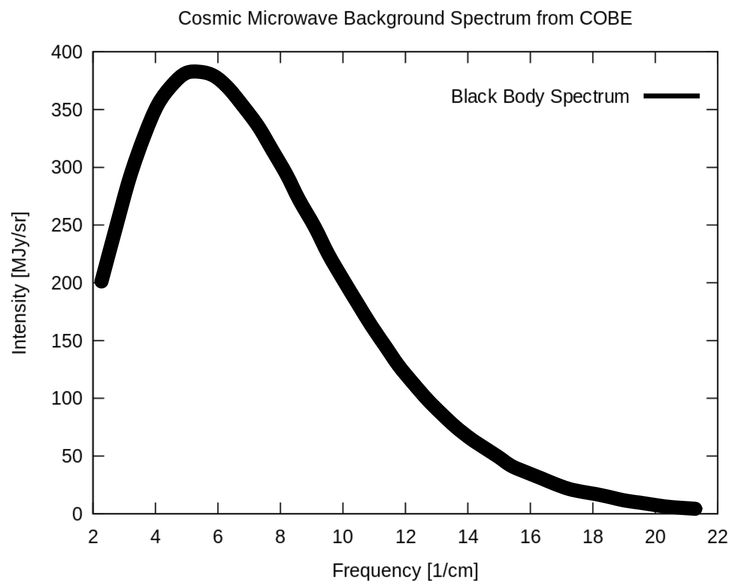
- black body radiation?

COBE satellite (1992):



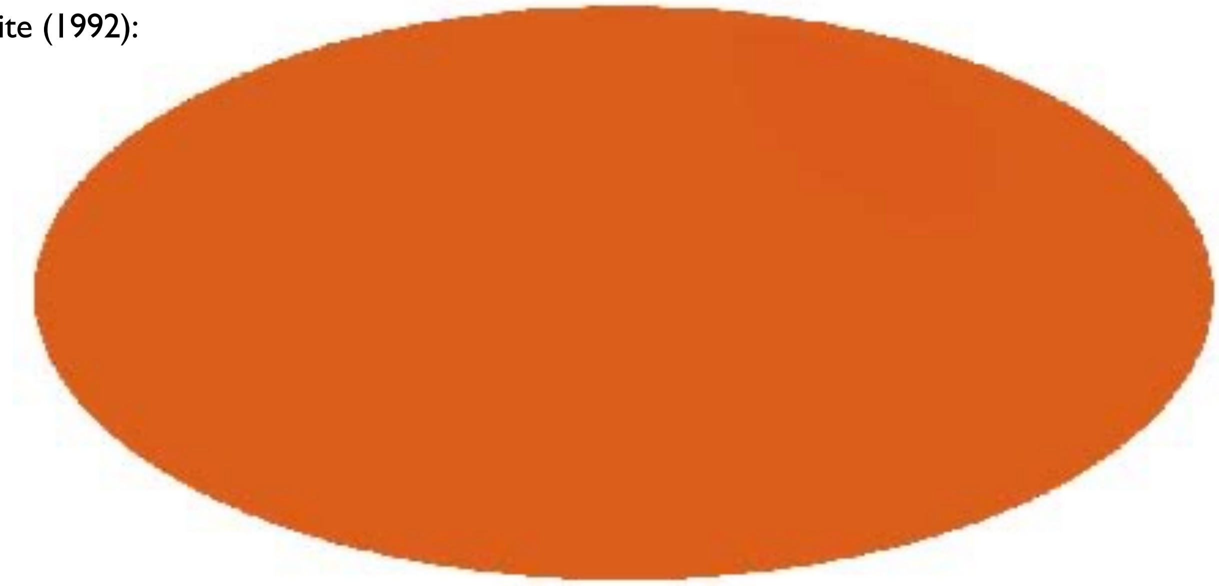
T = 2.725K

- measurements at various frequencies required!



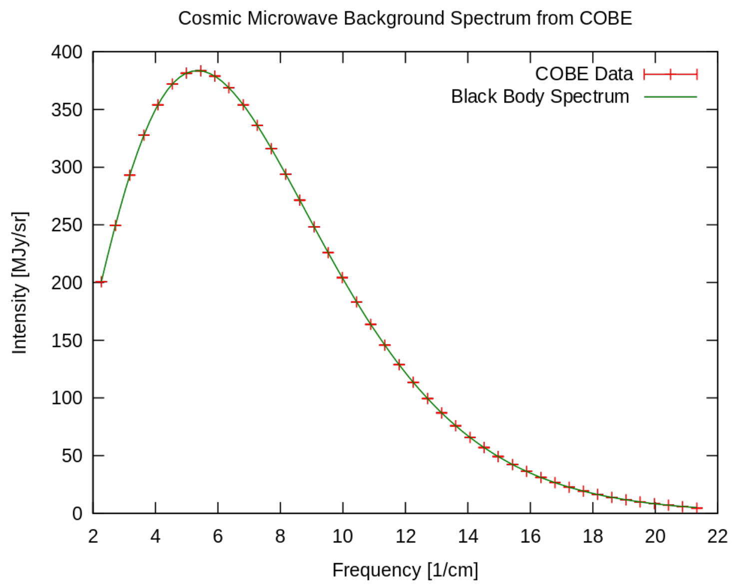
- black body radiation!

COBE satellite (1992):



T = 2.725K

- measurements at various frequencies required
- the most accurate black-body spectrum imaginable:

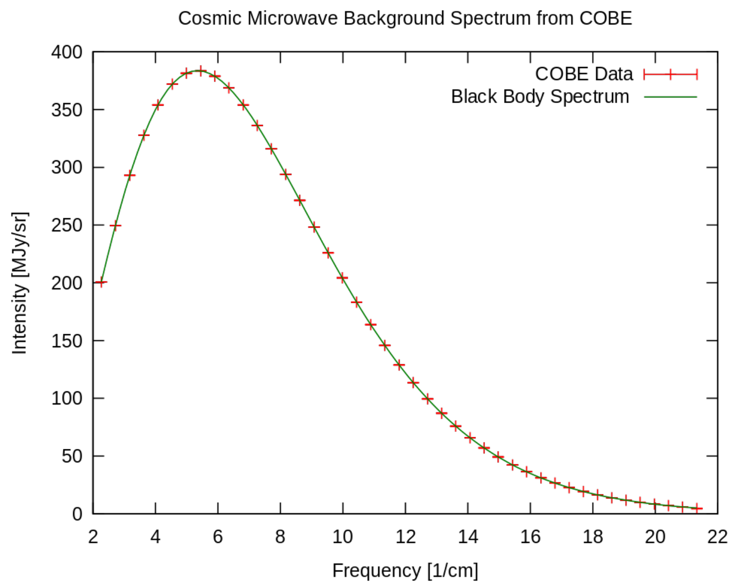


- black body radiation!

COBE satellite (1992):

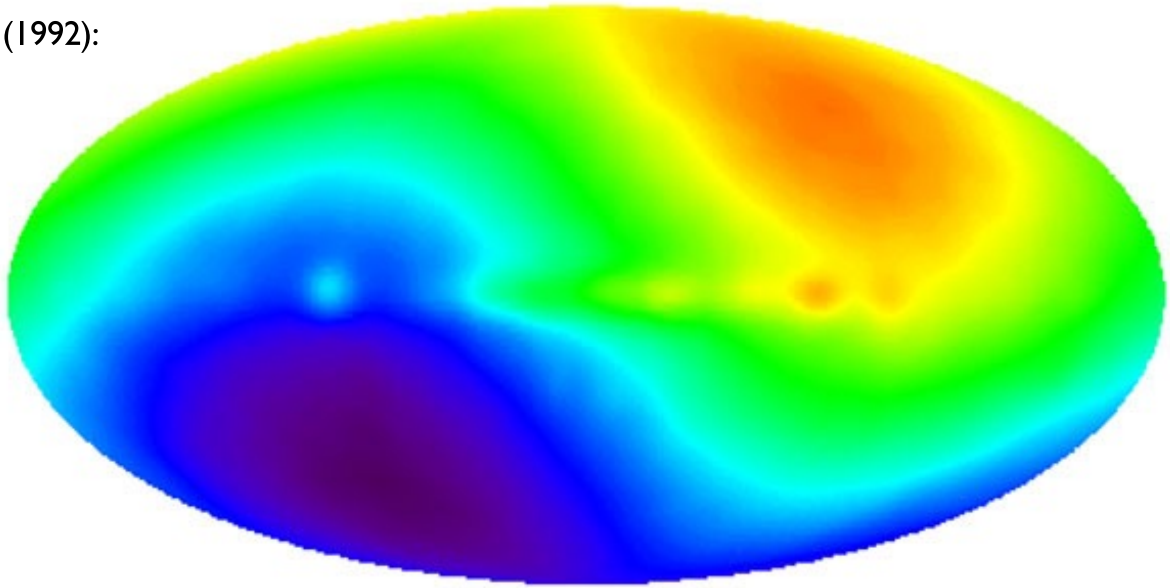
T = 2.725K

- measurements at various frequencies required
- the most accurate black-body spectrum imaginable:



- dipole…

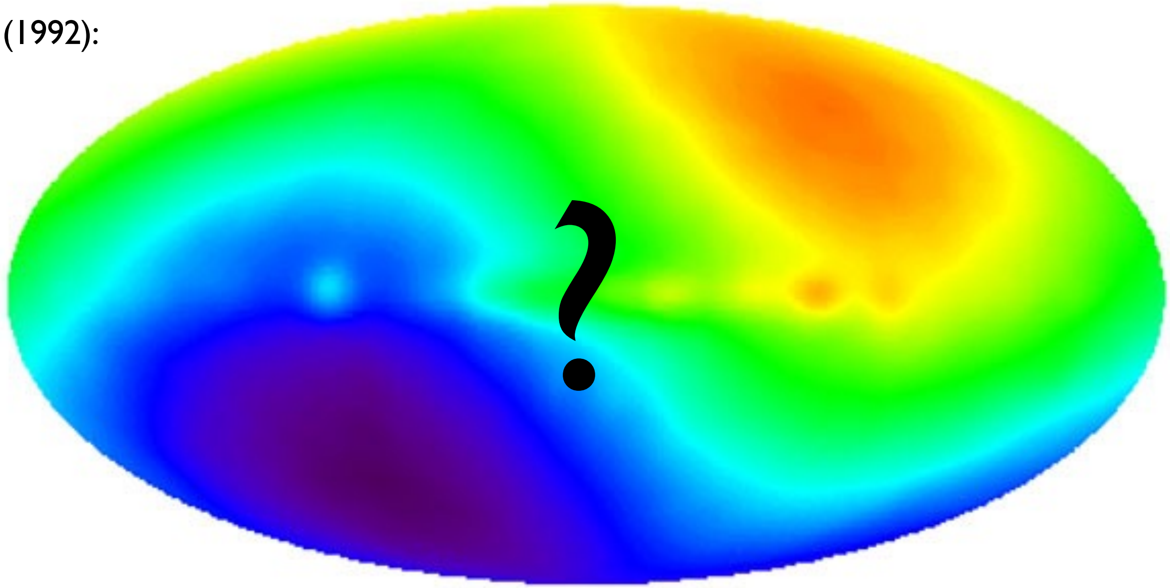
COBE satellite (1992):



$\Delta T = 3.353 mK$

- dipole…

COBE satellite (1992):

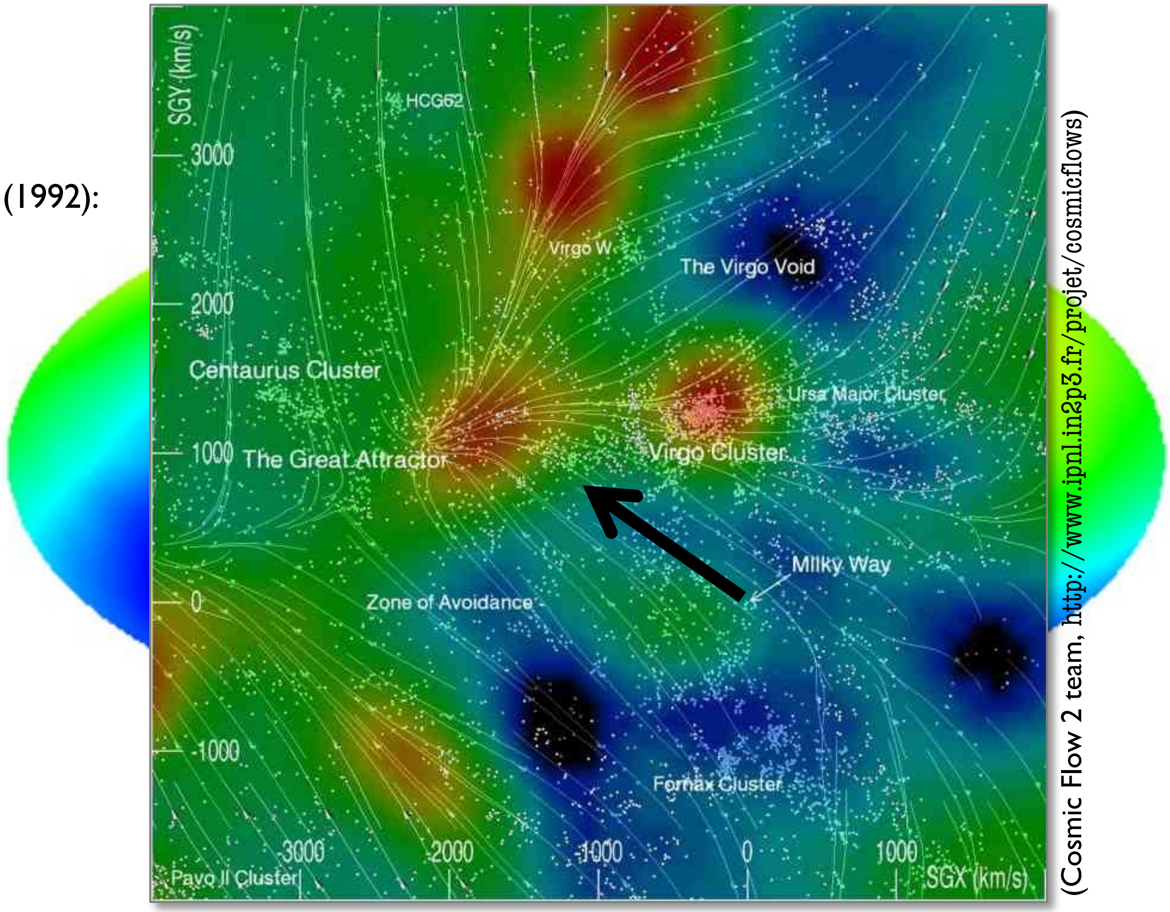


$\Delta T = 3.353\text{mK}$

Cosmic Microwave Background

- dipole…

COBE satellite (1992):

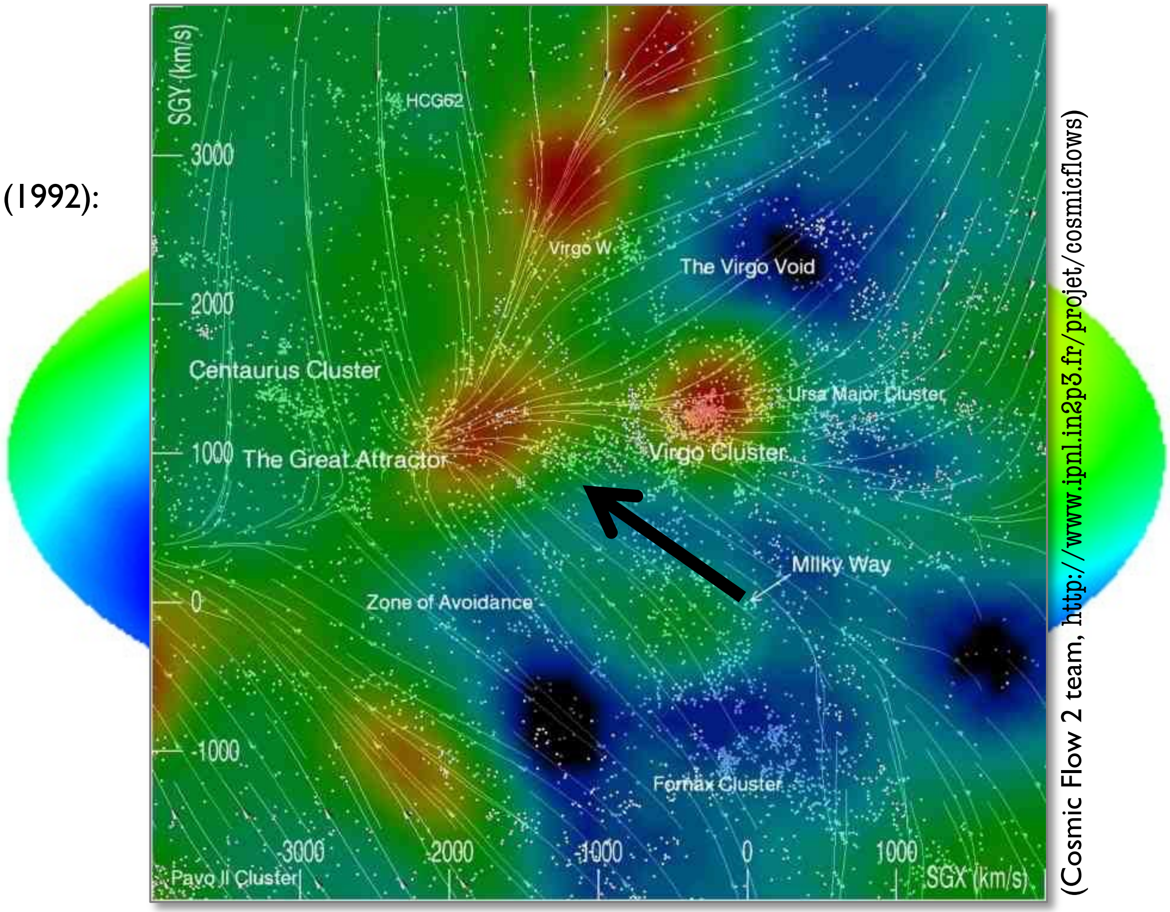


(Cosmic Flow 2 team, http://www.ipnl.in2p3.fr/projet/cosmicflows)

- caused by movement of Local Group towards the Great Attractor at ca. 627 km/s

- dipole…

COBE satellite (1992):



(Cosmic Flow 2 team, http://www.ipnl.in2p3.fr/projet/cosmicflows)

- caused by movement of Local Group towards the Great Attractor at ca. 627 km/s

  → a dipole has to exist unless MW is at rest with respects to CMB

- dipole…

COBE satellite (1992)

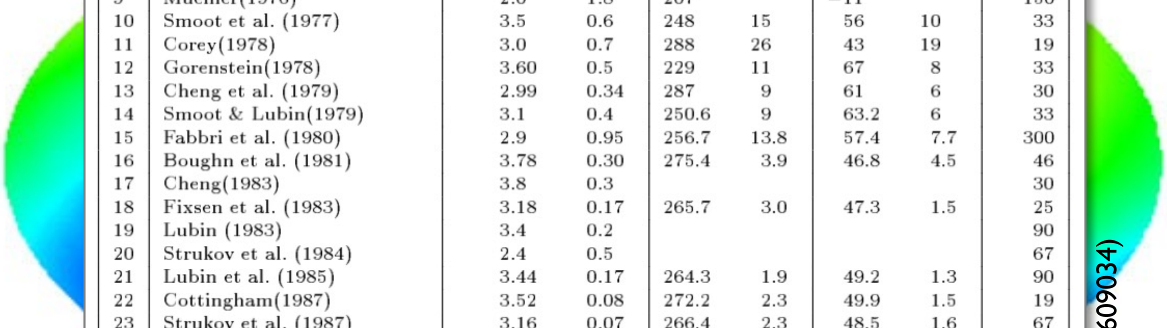


Table 1: CMB Dipole Measurements

#	Reference	Amplitude D(mK)	$\pm\sigma$	Longitude[a] ℓ(deg)	$\pm\sigma$	Latitude[a] b(deg)	$\pm\sigma$	Freq (GHz)
1	Penzias & Wilson(1965)	< 270						4
2	Partridge & Wilkinson(1967)	0.8	2.2					9
3	Wilkinson & Partridge(1969)	1.1	1.6					9
4	Conklin(1969)	1.6	0.8	96	30	85	30	8
5	Boughn et al. (1971)	7.6	11.6					37
6	Henry(1971)	3.3	0.7	270	30	24	25	10
7	Conklin(1972)	> 2.28	0.92	195	30	66	10	8
8	Corey & Wilkinson(1976)	2.4	0.6	306	28	38	20	19
9	Muehler(1976)	2.0	1.8	207		−11		150
10	Smoot et al. (1977)	3.5	0.6	248	15	56	10	33
11	Corey(1978)	3.0	0.7	288	26	43	19	19
12	Gorenstein(1978)	3.60	0.5	229	11	67	8	33
13	Cheng et al. (1979)	2.99	0.34	287	9	61	6	30
14	Smoot & Lubin(1979)	3.1	0.4	250.6	9	63.2	6	33
15	Fabbri et al. (1980)	2.9	0.95	256.7	13.8	57.4	7.7	300
16	Boughn et al. (1981)	3.78	0.30	275.4	3.9	46.8	4.5	46
17	Cheng(1983)	3.8	0.3					30
18	Fixsen et al. (1983)	3.18	0.17	265.7	3.0	47.3	1.5	25
19	Lubin (1983)	3.4	0.2					90
20	Strukov et al. (1984)	2.4	0.5					67
21	Lubin et al. (1985)	3.44	0.17	264.3	1.9	49.2	1.3	90
22	Cottingham(1987)	3.52	0.08	272.2	2.3	49.9	1.5	19
23	Strukov et al. (1987)	3.16	0.07	266.4	2.3	48.5	1.6	67
24	Halpern et al. (1988)	3.4	0.42	289.5	4.1	38.4	4.8	150
25	Meyer et al. (1991)			249.9	4.5	47.7	3.0	170
26	Smoot et al. (1991)	3.3	0.1	265	1	48	1	53
27	Smoot et al. (1992)	3.36	0.1	264.7	0.8	48.2	0.5	53
28	Ganga et al. (1993)			267.0	1.0	49.0	0.7	170
29	Kogut et al. (1993)	3.365	0.027	264.4	0.3	48.4	0.5	53
30	Fixsen et al. (1994)	3.347	0.008	265.6	0.75	48.3	0.5	300
31	Bennett et al. (1994)	3.363	0.024	264.4	0.2	48.1	0.4	53
32	Bennett et al. (1996)	3.353	0.024	264.26	0.33	48.22	0.13	53
33	Fixsen et al. (1996)	3.372	0.005	264.14	0.17	48.26	0.16	300
34	Lineweaver et al. (1996)	3.358	0.023	264.31	0.17	48.05	0.10	53

(Lineweaver, astro-ph/9609034)

- ...had been subject of lots of experiment since 1965:

→ a dipole has to exist unless MW is at rest with respects to CMB

- dipole…

COBE satellite (1992)

more in a few slides...

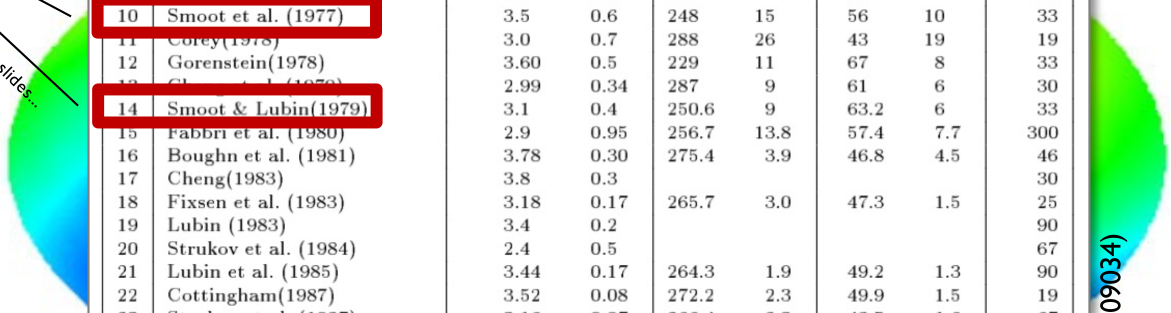


Table 1: CMB Dipole Measurements

#	Reference	Amplitude D(mK)	± σ	Longitude[a] ℓ(deg)	± σ	Latitude[a] b(deg)	± σ	Freq (GHz)
1	Penzias & Wilson(1965)	< 270						4
2	Partridge & Wilkinson(1967)	0.8	2.2					9
3	Wilkinson & Partridge(1969)	1.1	1.6					9
4	Conklin(1969)	1.6	0.8	96	30	85	30	8
5	Boughn et al. (1971)	7.6	11.6					37
6	Henry(1971)	3.3	0.7	270	30	24	25	10
7	Conklin(1972)	> 2.28	0.92	195	30	66	10	8
8	Corey & Wilkinson(1976)	2.4	0.6	306	28	38	20	19
9	Muehler(1976)	2.0	1.8	207		−11		150
10	Smoot et al. (1977)	3.5	0.6	248	15	56	10	33
11	Corey(1978)	3.0	0.7	288	26	43	19	19
12	Gorenstein(1978)	3.60	0.5	229	11	67	8	33
13	Cheng et al. (1979)	2.99	0.34	287	9	61	6	30
14	Smoot & Lubin(1979)	3.1	0.4	250.6	9	63.2	6	33
15	Fabbri et al. (1980)	2.9	0.95	256.7	13.8	57.4	7.7	300
16	Boughn et al. (1981)	3.78	0.30	275.4	3.9	46.8	4.5	46
17	Cheng(1983)	3.8	0.3					30
18	Fixsen et al. (1983)	3.18	0.17	265.7	3.0	47.3	1.5	25
19	Lubin (1983)	3.4	0.2					90
20	Strukov et al. (1984)	2.4	0.5					67
21	Lubin et al. (1985)	3.44	0.17	264.3	1.9	49.2	1.3	90
22	Cottingham(1987)	3.52	0.08	272.2	2.3	49.9	1.5	19
23	Strukov et al. (1987)	3.16	0.07	266.4	2.3	48.5	1.6	67
24	Halpern et al. (1988)	3.4	0.42	289.5	4.1	38.4	4.8	150
25	Meyer et al. (1991)			249.9	4.5	47.7	3.0	170
26	Smoot et al. (1991)	3.3	0.1	265	1	48	1	53
27	Smoot et al. (1992)	3.36	0.1	264.7	0.8	48.2	0.5	53
28	Ganga et al. (1993)			267.0	1.0	49.0	0.7	170
29	Kogut et al. (1993)	3.365	0.027	264.4	0.3	48.4	0.5	53
30	Fixsen et al. (1994)	3.347	0.008	265.6	0.75	48.3	0.5	300
31	Bennett et al. (1994)	3.363	0.024	264.4	0.2	48.1	0.4	53
32	Bennett et al. (1996)	3.353	0.024	264.26	0.33	48.22	0.13	53
33	Fixsen et al. (1996)	3.372	0.005	264.14	0.17	48.26	0.16	300
34	Lineweaver et al. (1996)	3.358	0.023	264.31	0.17	48.05	0.10	53

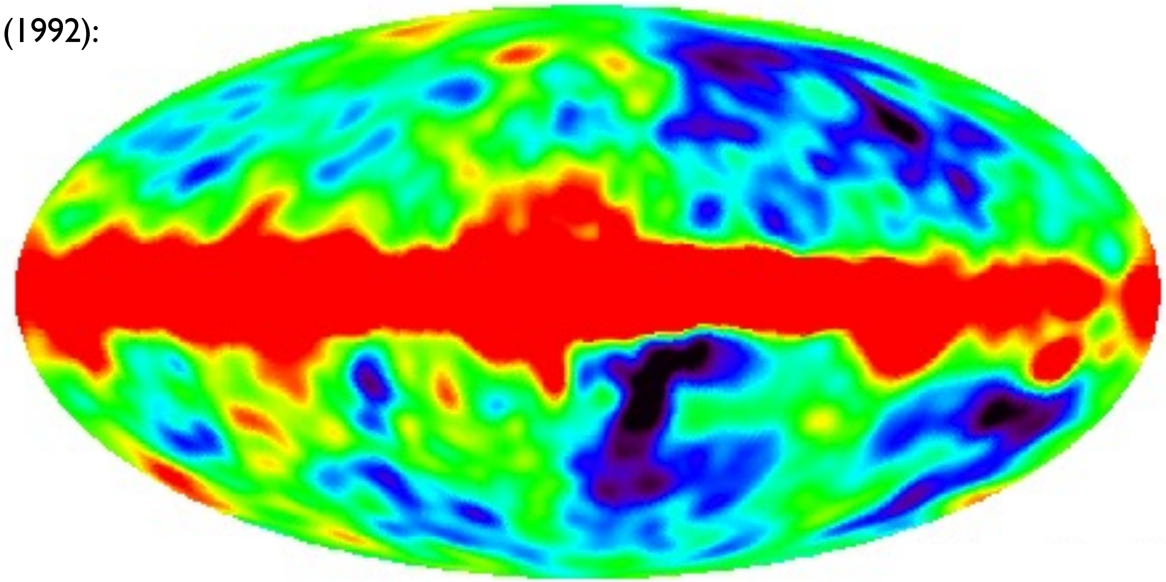
(Lineweaver, astro-ph/9609034)

- ...had been subject of lots of experiment since 1965:

→ a dipole has to exist unless MW is at rest with respects to CMB

- …and lots of higher order anisotropies, too!

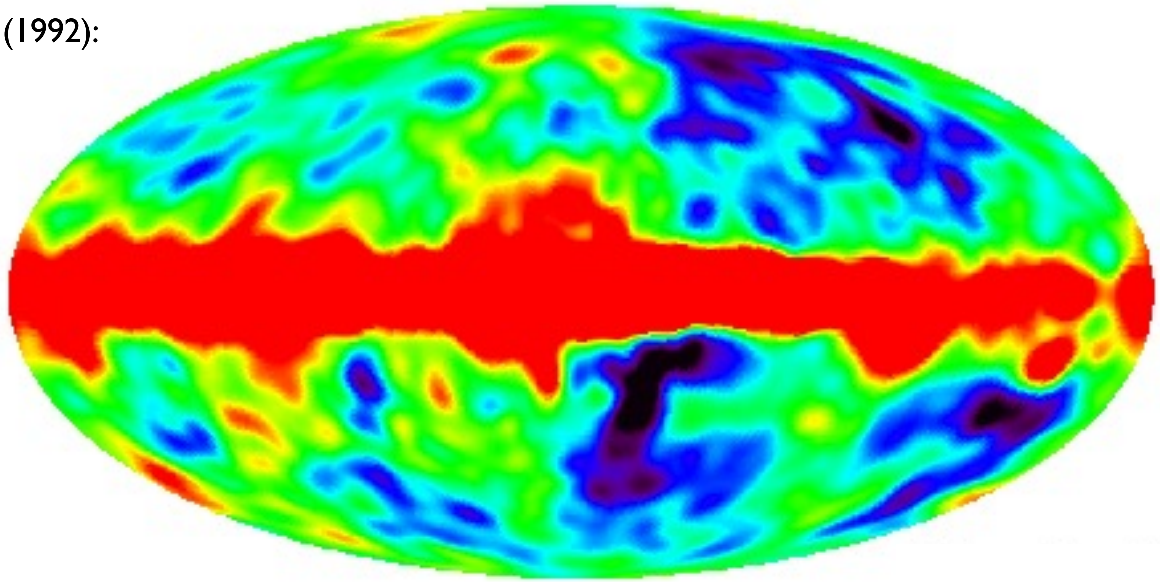
COBE satellite (1992):



$\Delta T = 18\mu K$

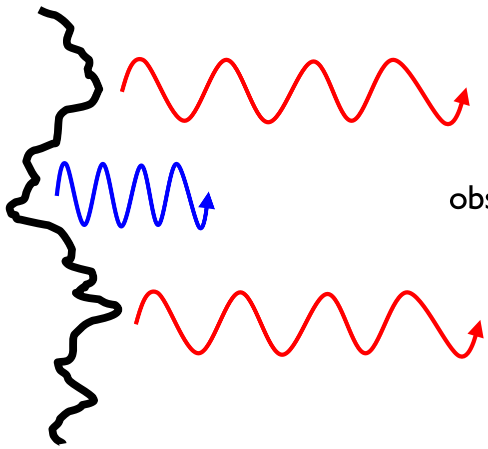
- …and lots of higher order anisotropies, too:

COBE satellite (1992):



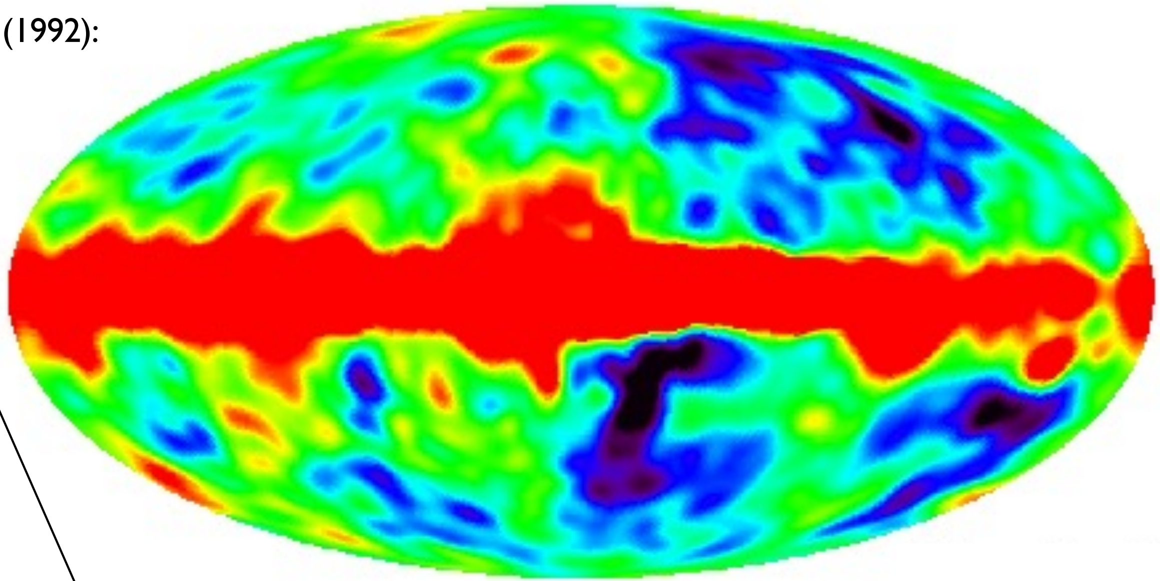
$\Delta T = 18\mu K$

- imprint of primordial density inhomogeneities!



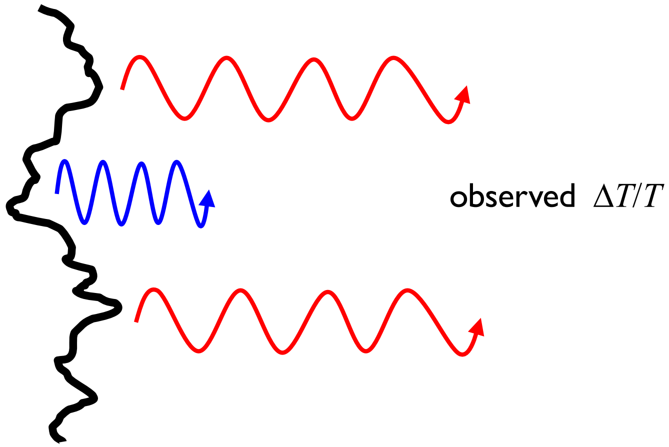
- …and lots of higher order anisotropies, too:

COBE satellite (1992):



$\Delta T = 18 \mu K$

- imprint of primordial density inhomogeneities!
- Nobel prize for ***COBE*** PI's Smoot & Mather in 2006



- list of selected CMB missions to measure anisotropies

  - 1990: launch of COBE satellite (Nobel prize in 2006 for discovery of $\Delta T/T$)
  - 1999: BOOMERanG and Maxima balloon experiments
  - 2001: launch of WMAP satellite
  - 2002: DASI discovers polarisation
  - 2009: launch of Planck satellite

- list of selected CMB missions to measure anisotropies

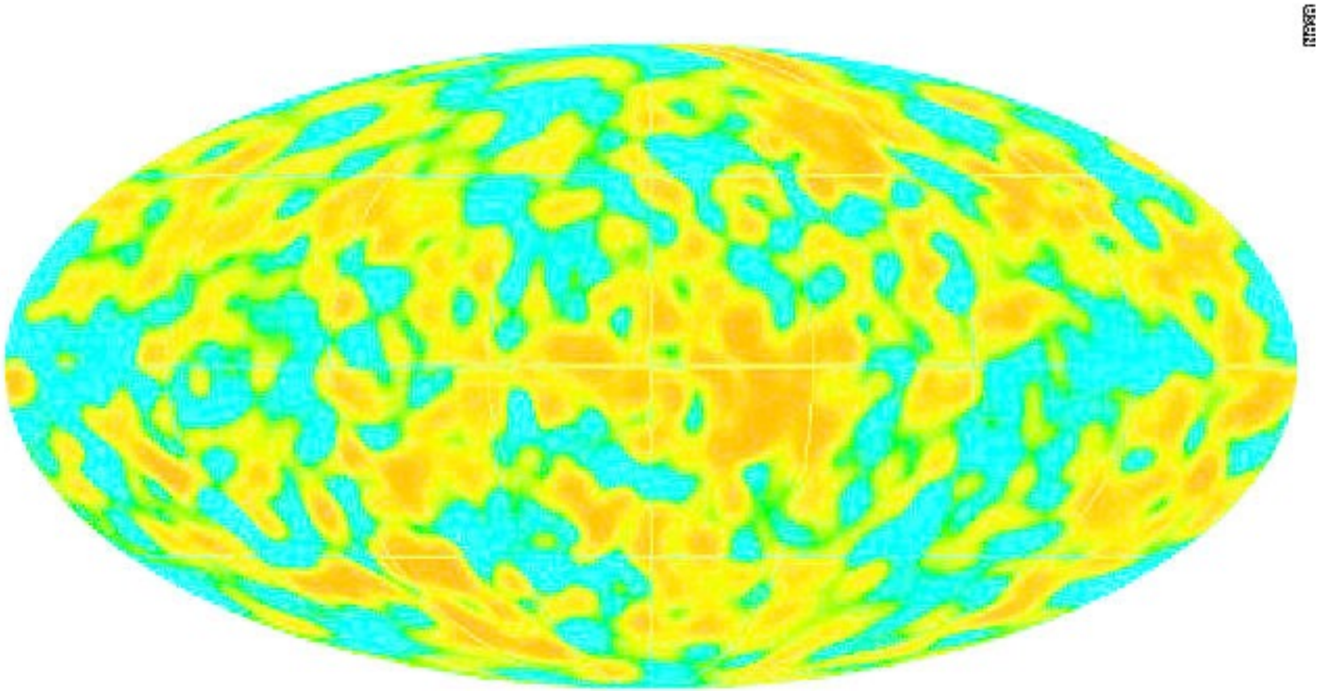
  - 1983: launch of Russian satellite RELIKT-1 (announced discovery of $\Delta T/T$ in 1992…)
  - 1990: launch of COBE satellite (Nobel prize in 2006 for discovery of $\Delta T/T$)
  - 1999: BOOMERanG and Maxima balloon experiments
  - 2001: launch of WMAP satellite
  - 2002: DASI discovers polarisation
  - 2009: launch of Planck satellite

- list of selected CMB missions to measure anisotropies

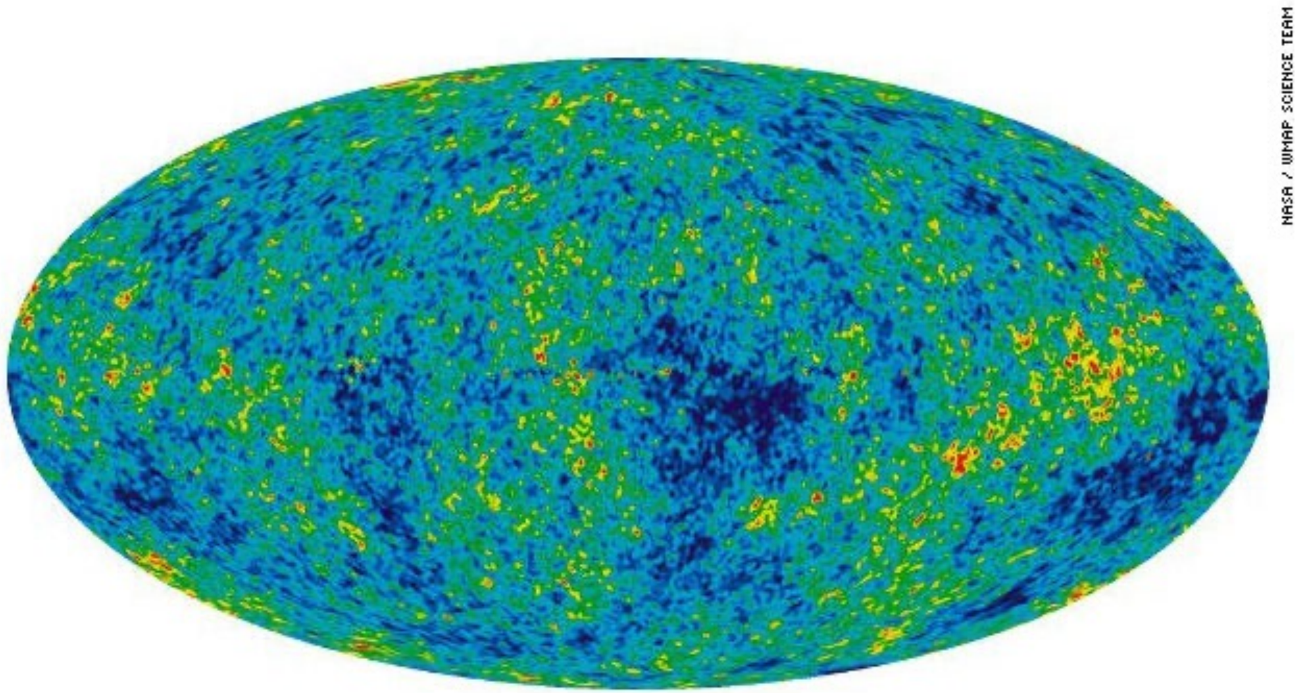
  - 1983: launch of Russian satellite RELIKT-1 (announced discovery of $\Delta T/T$ in 1992…)
  - 1990: launch of **COBE** satellite (Nobel prize in 2006 for discovery of $\Delta T/T$)
  - 1999: BOOMERanG and Maxima balloon experiments
  - 2001: launch of **WMAP** satellite
  - 2002: DASI discovers polarisation
  - 2009: launch of **Planck** satellite

improvement in accuracy!?

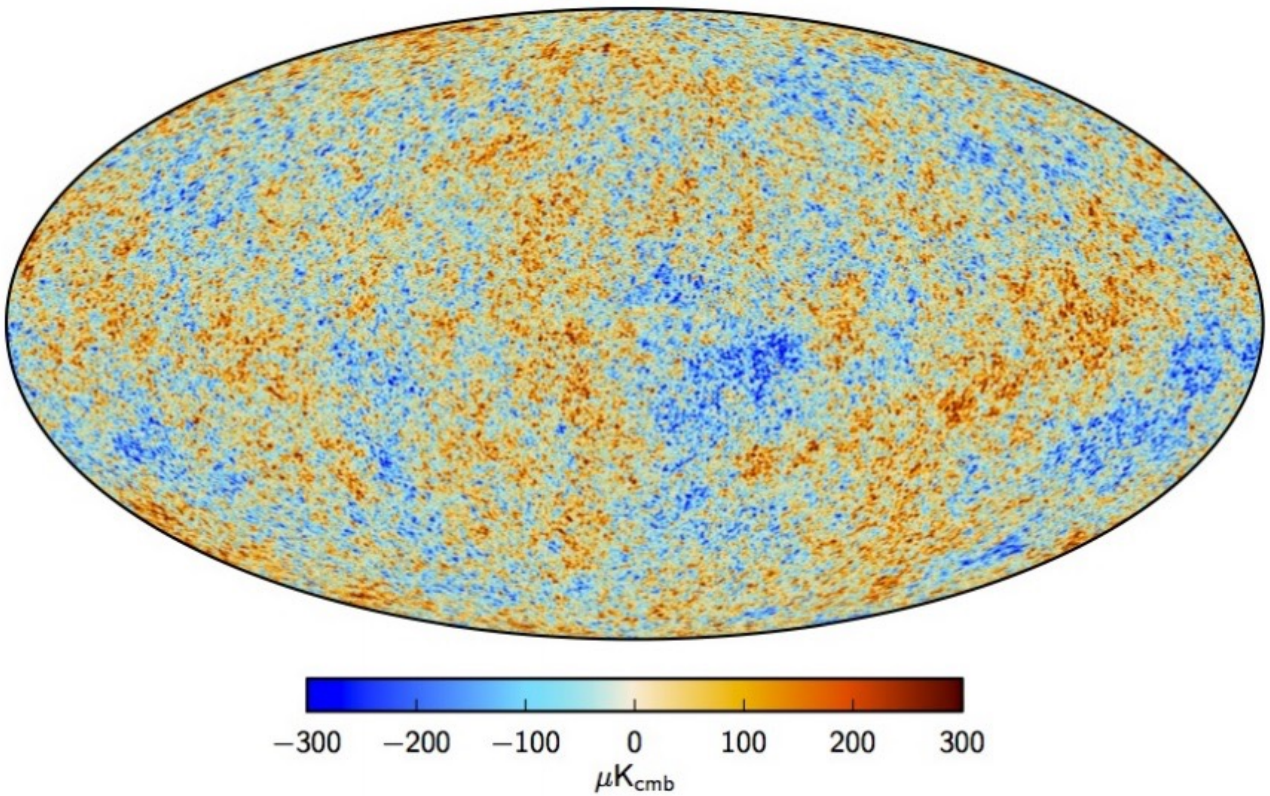
- anisotropies as measured by COBE (1992):



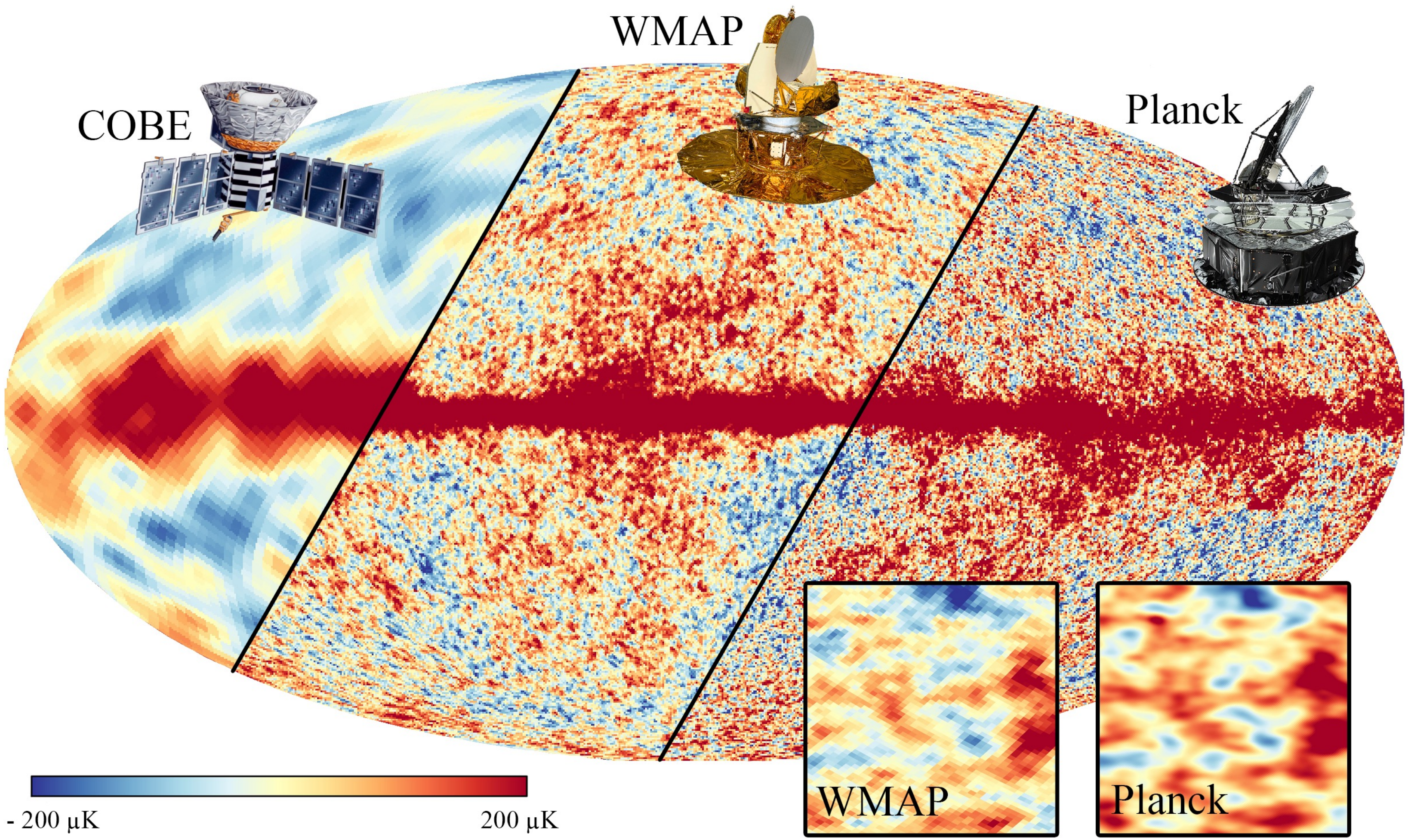
- anisotropies as measured by WMAP (2001):



- anisotropies as measured by Planck (2015):

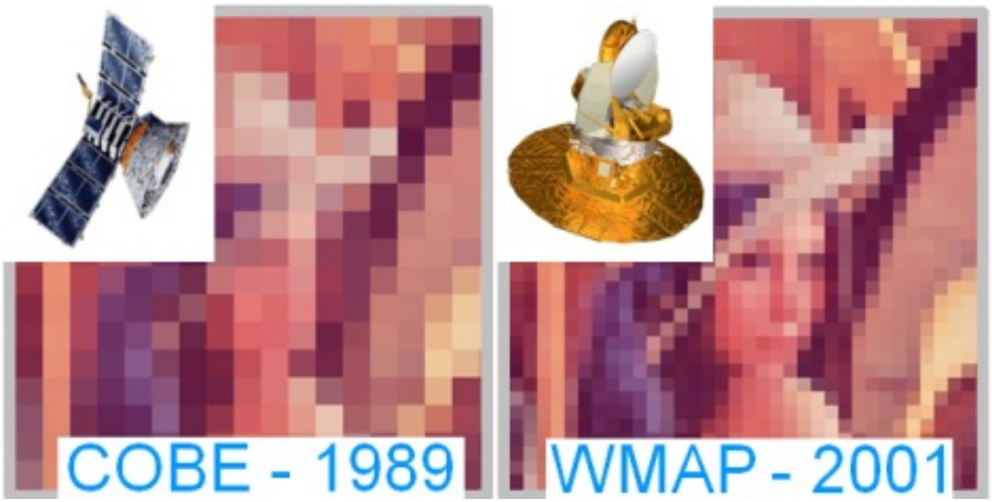


- anisotropies as measured in comparison:



- accuracies in comparison:

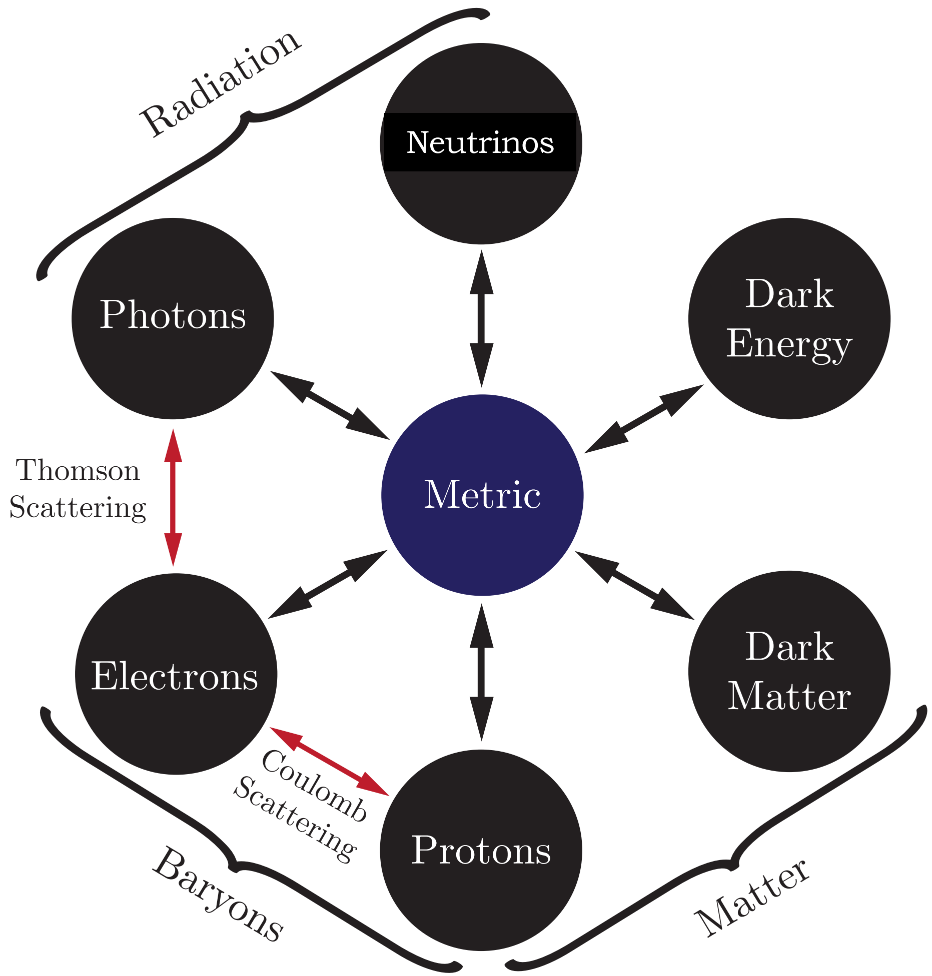
- accuracies in comparison:



- accuracies in comparison:

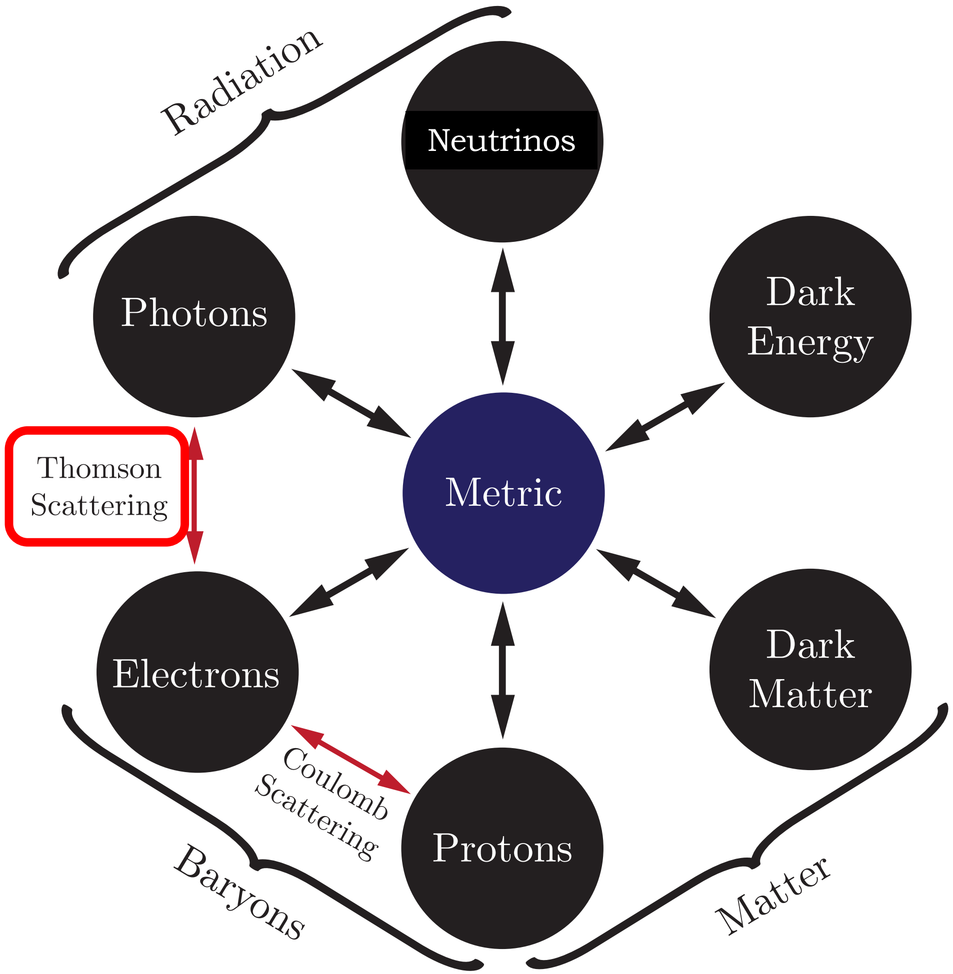
- discovery
- **origin**
- CMB fluctuations
  - primary (created during inflation)
  - secondary (created after photon decoupling)

- interactions between different forms of matter

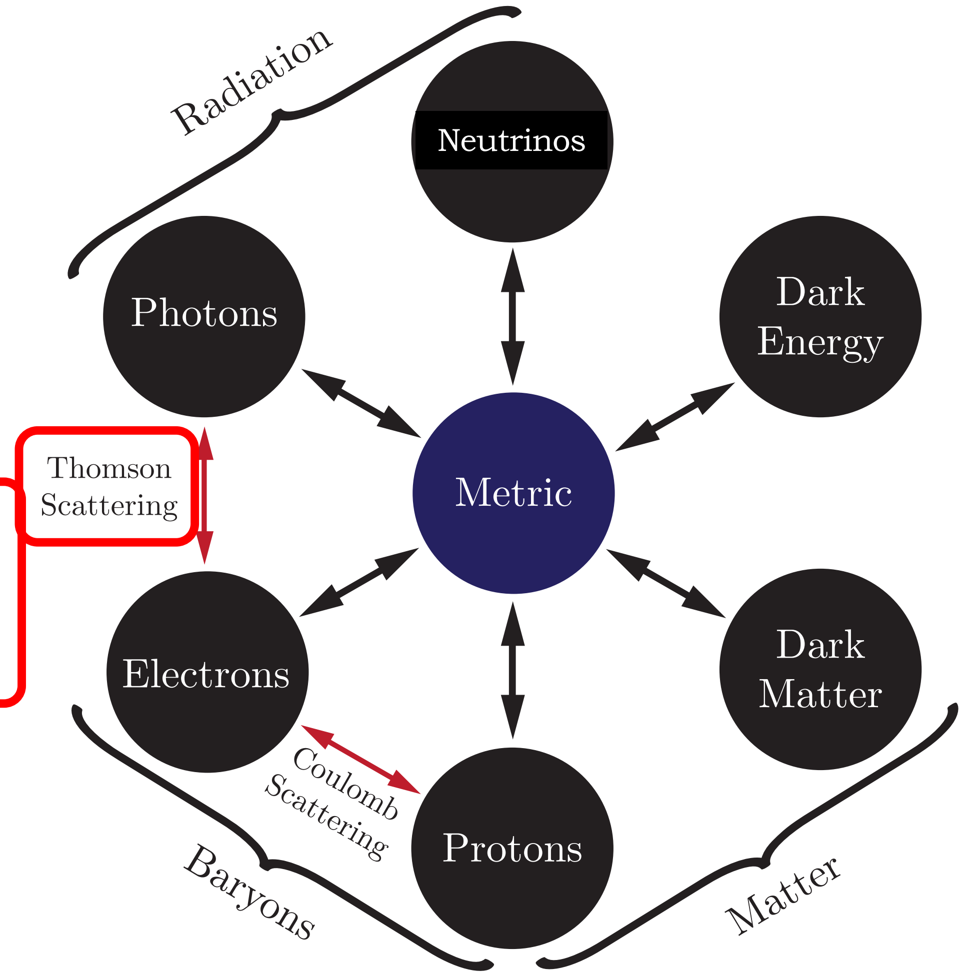


- interactions between different forms of matter

only for as long as there are free electrons



- interactions between different forms of matter



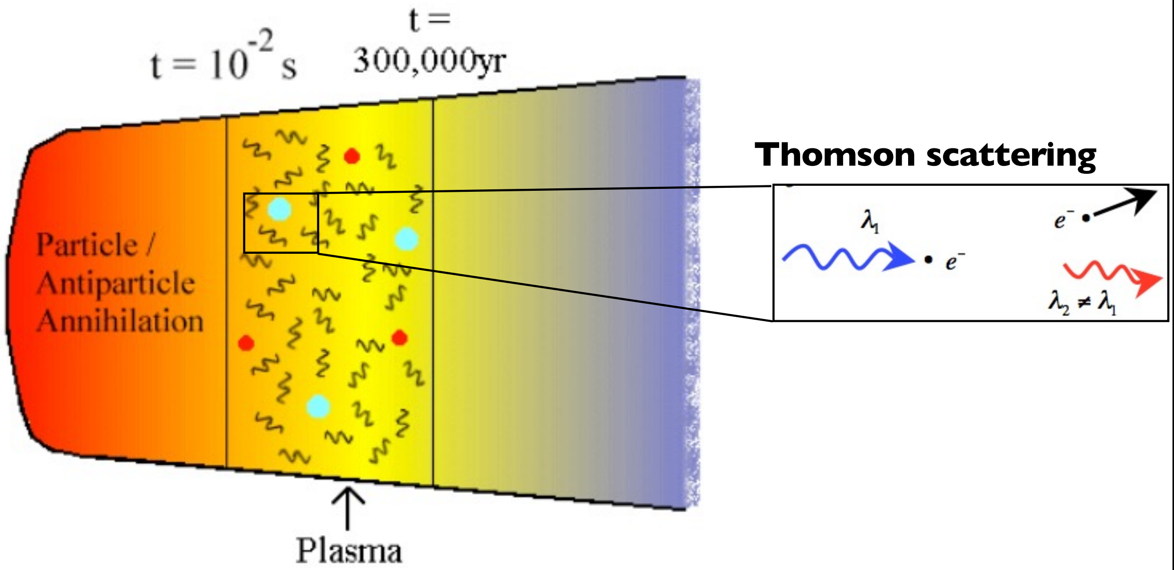
only for as long as there are free electrons

even after e^--e^+ annihilation there are electrons left…
(cf. Baryogenesis lecture)

- CMBR origin

prior to recombination

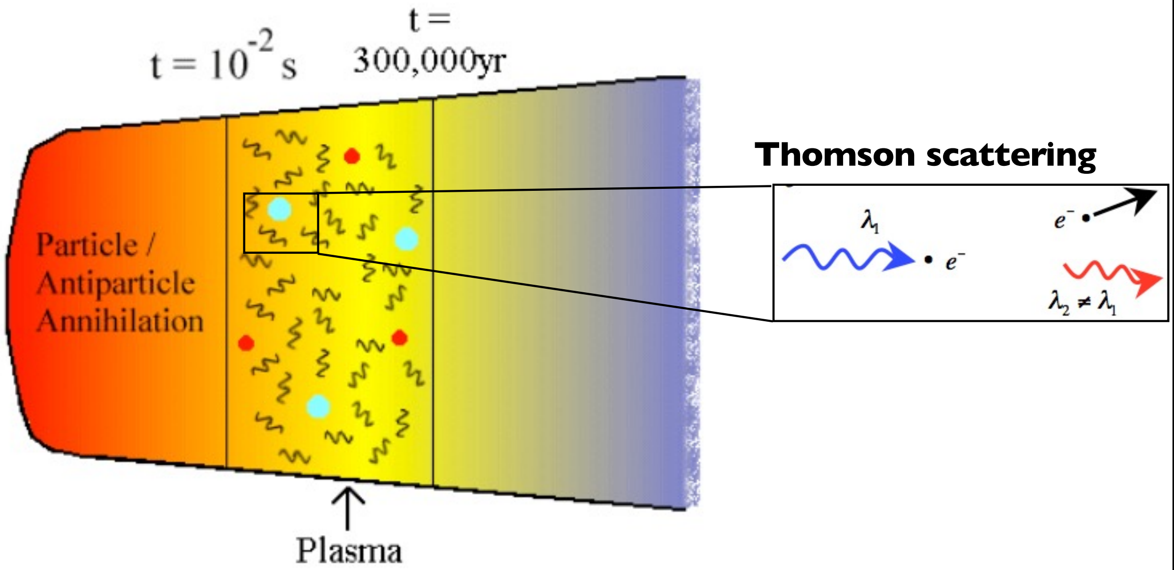
- electrons and photons couple via Thomson scattering
- Universe is opaque for radiation



- CMBR origin

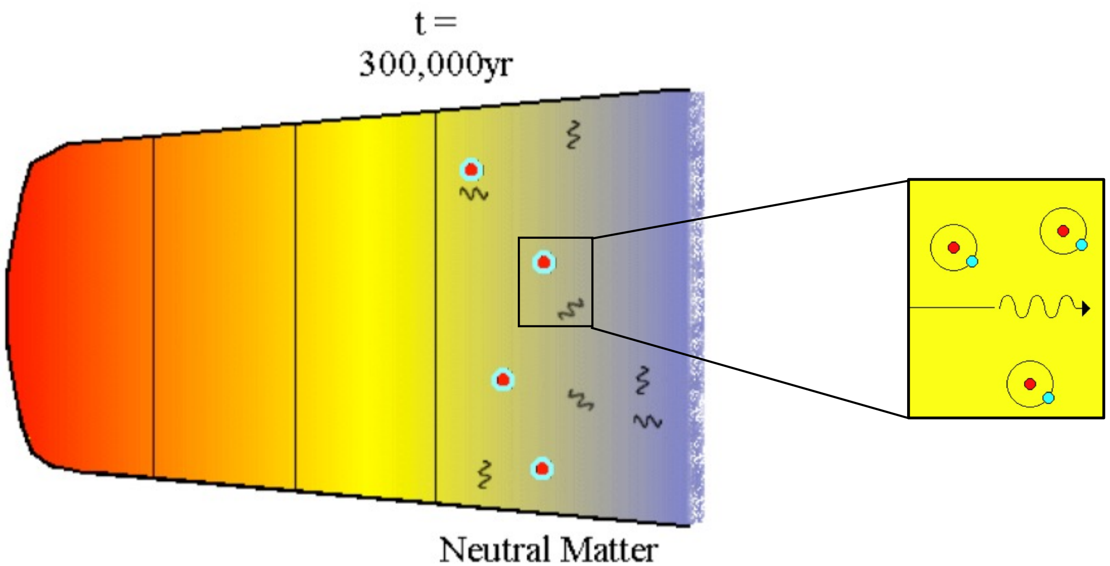
prior to recombination

- electrons and photons couple via Thomson scattering
- Universe is opaque for radiation



after decoupling

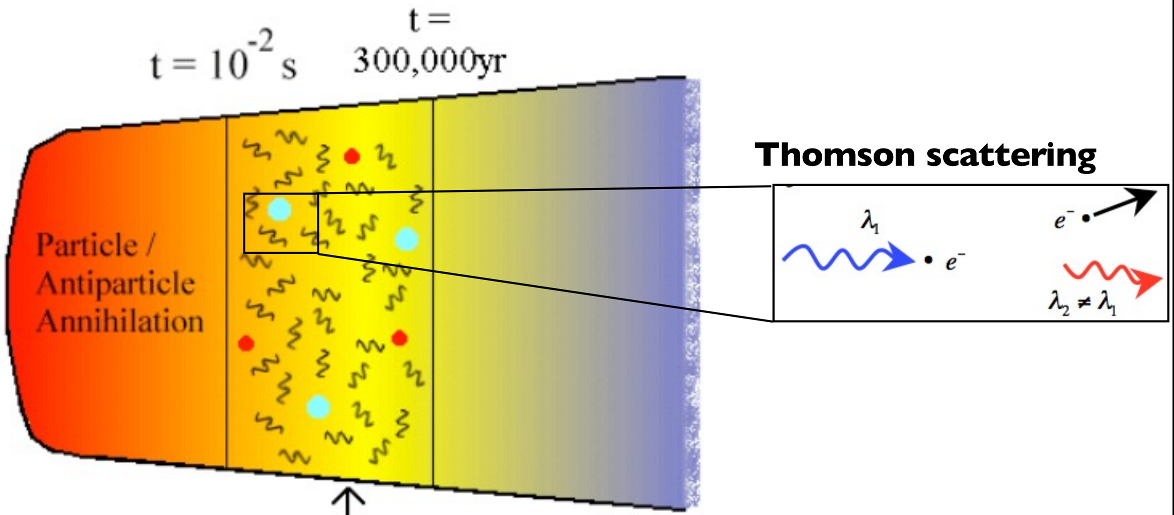
- electrons are bound to protons
- photons are free to travel



- CMBR origin

prior to *recombination*

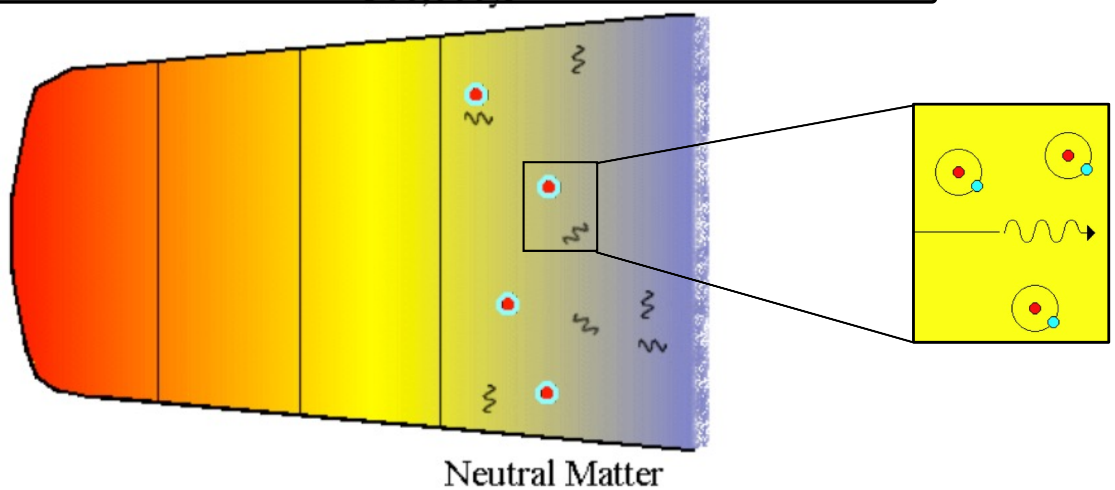
- electrons and photons couple via Thomson scattering
- Universe is opaque for radiation



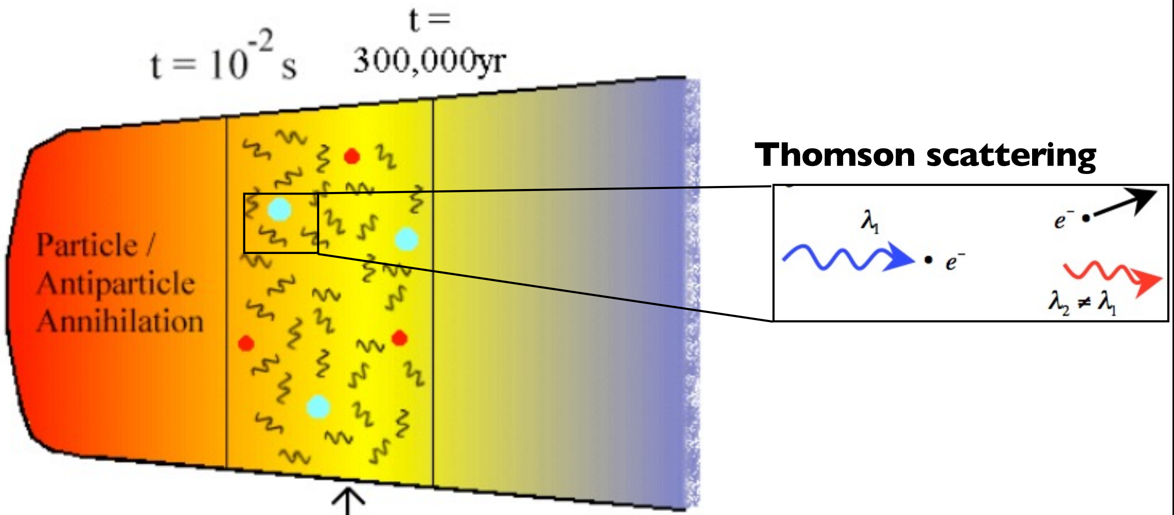
***recombination* and *decoupling* are not the same and happen at different times…**

after *decoupling*

- electrons are bound to protons
- photons are free to travel



- CMBR origin

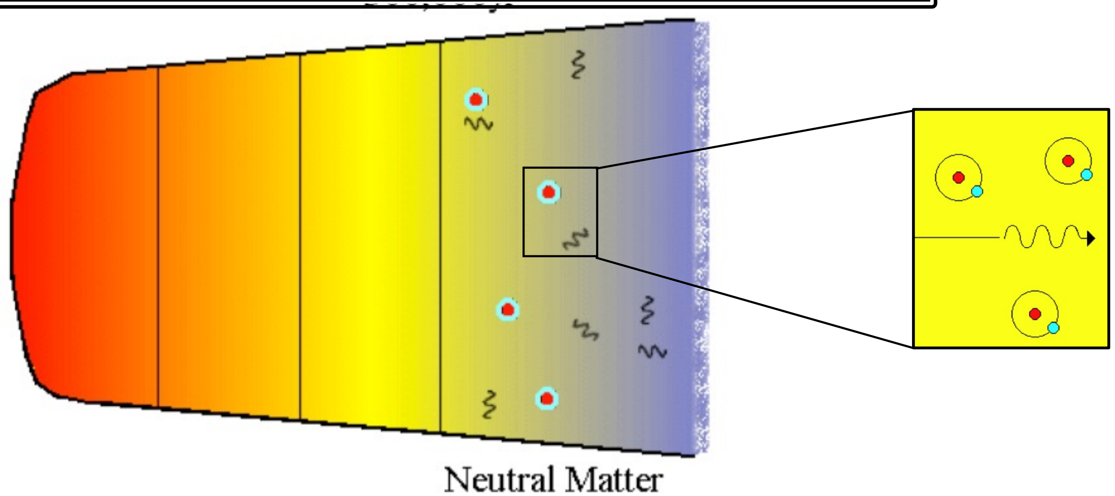


prior to *recombination*

- electrons and photons couple via Thomson scattering
- Universe is opaque for radiation

At what temperatures will this happen?

***recombination* and *decoupling* are not the same and happen at different times...**



after *decoupling*

- electrons are bound to protons
- photons are free to travel

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

- CMBR origin calculation – hydrogen recombination

$$e^{-} + p \leftrightarrow H + \gamma$$

we are interested in the fraction of free electrons:

those are the ones participating in the scattering with photons!

$$e^{-} + \gamma \leftrightarrow e^{-} + \gamma$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$n_e = g_e \left(\frac{m_e kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_e - \mu_e)c^2/kT}$$

$$n_p = g_p \left(\frac{m_p kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_p - \mu_p)c^2/kT}$$

$$n_H = g_H \left(\frac{m_H kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_H - \mu_H)c^2/kT}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} \left(\frac{k}{\hbar c} \right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$\left.\begin{aligned} n_e &= g_e \left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_e-\mu_e)c^2/kT} \\ n_p &= g_p \left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_p-\mu_p)c^2/kT} \\ n_H &= g_H \left(\frac{m_H kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_H-\mu_H)c^2/kT} \end{aligned}\right\} \left(\frac{n_H}{n_e n_p}\right)$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$n_e = g_e \left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_e-\mu_e)c^2/kT}$$

$$n_p = g_p \left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_p-\mu_p)c^2/kT}$$

$$n_H = g_H \left(\frac{m_H kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_H-\mu_H)c^2/kT}$$

$$\left\} \quad \left(\frac{n_H}{n_e n_p}\right)\right.$$

$$\mu_e + \mu_p = \mu_H \; ; \quad \mu_\gamma = 0$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$n_e = g_e \left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_e-\mu_e)c^2/kT}$$

$$n_p = g_p \left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_p-\mu_p)c^2/kT}$$

$$n_H = g_H \left(\frac{m_H kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_H-\mu_H)c^2/kT}$$

$$\left(\frac{n_H}{n_e n_p}\right) = \frac{g_H}{g_e g_p}\left(\frac{m_H}{m_e m_p}\frac{2\pi\hbar^2}{kT}\right)^{3/2} e^{(m_e+m_p-m_H)c^2/kT}$$

$$\mu_e + \mu_p = \mu_H \; ; \quad \mu_\gamma = 0$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$n_e = g_e \left(\frac{m_e kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_e-\mu_e)c^2/kT}$$

$$n_p = g_p \left(\frac{m_p kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_p-\mu_p)c^2/kT}$$

$$n_H = g_H \left(\frac{m_H kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_H-\mu_H)c^2/kT}$$

$$\left(\frac{n_H}{n_e n_p} \right) = \frac{g_H}{g_e g_p} \left(\frac{m_H}{m_e m_p} \frac{2\pi\hbar^2}{kT} \right)^{3/2} e^{\underbrace{(m_e+m_p-m_H)c^2}/kT}$$

B_H: binding energy of hydrogen

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} \left(\frac{k}{\hbar c} \right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$\left.\begin{aligned}
n_e &= g_e \left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_e-\mu_e)c^2/kT} \\
n_p &= g_p \left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_p-\mu_p)c^2/kT} \\
n_H &= g_H \left(\frac{m_H kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_H-\mu_H)c^2/kT}
\end{aligned}\right\} \quad \left(\frac{n_H}{n_e n_p}\right) = \frac{g_H}{g_e g_p}\left(\frac{m_H}{m_e m_p}\frac{2\pi\hbar^2}{kT}\right)^{3/2} e^{B_H/kT}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$n_e = g_e \left(\frac{m_e kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_e-\mu_e)c^2/kT}$$

$$n_p = g_p \left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_p-\mu_p)c^2/kT}$$

$$n_H = g_H \left(\frac{m_H kT}{2\pi\hbar^2}\right)^{3/2} e^{-(m_H-\mu_H)c^2/kT}$$

$$\left(\frac{n_H}{n_e n_p}\right) = \frac{g_H}{g_e g_p}\left(\frac{m_H}{m_e m_p}\frac{2\pi\hbar^2}{kT}\right)^{3/2} e^{B_H/kT}$$

$n_e = n_p$ (charge neutrality)

$m_H \approx m_p$ (only for pre-factor!)

$g_e = g_p = 2$ (spin up/down)

$g_H = 4$ (e aligned/anti-aligned to p)

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$n_e = g_e \left(\frac{m_e kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_e - \mu_e)c^2/kT}$$

$$n_p = g_p \left(\frac{m_p kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_p - \mu_p)c^2/kT}$$

$$n_H = g_H \left(\frac{m_H kT}{2\pi\hbar^2} \right)^{3/2} e^{-(m_H - \mu_H)c^2/kT}$$

$$\left(\frac{n_H}{n_e^2} \right) = \left(\frac{2\pi\hbar^2}{m_e kT} \right)^{3/2} e^{B_H/kT}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} \left(\frac{k}{\hbar c} \right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^{-} + p \leftrightarrow H + \gamma$$

$$\left(\frac{n_H}{n_e^2}\right) = \left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^{-} + p \leftrightarrow H + \gamma$$

fraction of free electrons:

$$\left(\frac{n_H}{n_e^2}\right) = \left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$X_e = \frac{n_e}{n_b}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

fraction of free electrons:

$$\left(\frac{n_H}{n_e^2}\right) = \left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$X_e = \frac{n_e}{n_b} \; ?$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

fraction of free electrons:

$$\left(\frac{n_H}{n_e^2}\right) = \left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$X_e = \frac{n_e}{n_b}$$

$$n_b = \eta n_\gamma = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$\left(\frac{n_H}{n_e^2}\right) = \left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

fraction of free electrons:

$$X_e = \frac{n_e}{n_b}$$

$$n_b = \eta n_\gamma = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

$$n_b \approx n_p + n_H = n_e + n_H$$

(ignoring all nuclei A>1 and assuming charge neutrality)

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$\left(\frac{n_H}{n_e^2}\right) = \left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

fraction of free electrons:

$$X_e = \frac{n_e}{n_b}$$

$$n_b = \eta n_\gamma = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

$$n_b \approx n_p + n_H = n_e + n_H$$

(ignoring all nuclei A>1 and assuming charge neutrality)

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$\left(\frac{n_H}{n_e^2}\right) = \left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

fraction of free electrons:

$$X_e = \frac{n_e}{n_b}$$

$$n_b = \eta n_\gamma = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

$$n_b \approx n_p + n_H = n_e + n_H$$

$$n_H = n_e^2 \left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

$$\left(\frac{n_H}{n_e^2}\right) = \left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

fraction of free electrons:

$$X_e = \frac{n_e}{n_b}$$

$$n_b = \eta n_\gamma = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3 = n_e\left(1 + n_e\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}\right)$$

$$n_b \approx n_p + n_H = n_e + n_H$$

$$n_H = n_e^2\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

- CMBR origin calculation – hydrogen recombination

$$e^{-} + p \leftrightarrow H + \gamma$$

fraction of free electrons:

$$1 = \frac{X_e n_b}{n_e} \longleftarrow X_e = \frac{n_e}{n_b}$$

$$n_b = \eta n_\gamma = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3 \quad = n_e\left(1 + n_e\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}\right)$$

$$n_b \approx n_p + n_H = n_e + n_H$$

$$n_H = n_e^2\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

fraction of free electrons:

$$1 = \frac{X_e n_b}{n_e} \leftarrow X_e = \frac{n_e}{n_b}$$

$$n_b = \eta n_\gamma = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3 = n_e\left(1 + n_e\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}\right)$$

$$n_b \approx n_p + n_H = n_e + n_H$$

$$n_H = n_e^2\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

fraction of free electrons:

$$X_e = \frac{n_e}{n_b}$$

$$n_b = \eta n_\gamma = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3 \quad = n_e\left(1 + n_e\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}\right)$$

$$n_b \approx n_p + n_H \;= n_e + n_H$$

$$n_H = n_e^2\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$1 = X_e\left(1 + n_e\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}\right)$$

$$\frac{1}{X_e} = 1 + n_e\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$\frac{1}{X_e} - 1 = n_e\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$\frac{1-X_e}{X_e} = n_e\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT} = X_e n_b\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

$$\frac{1-X_e}{X_e^2} = \eta\frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3\left(\frac{2\pi\hbar^2}{m_e kT}\right)^{3/2} e^{B_H/kT}$$

- CMBR origin calculation – hydrogen recombination

$$e^- + p \leftrightarrow H + \gamma$$

fraction of free electrons:

$$\frac{1-X_e}{X_e^2} = \frac{2\zeta(3)}{\pi^2}\eta\left(\frac{2\pi kT}{c^2 m_e}\right)^{3/2} e^{B_H/kT}$$

(Saha equation)

- CMBR origin calculation – hydrogen recombination

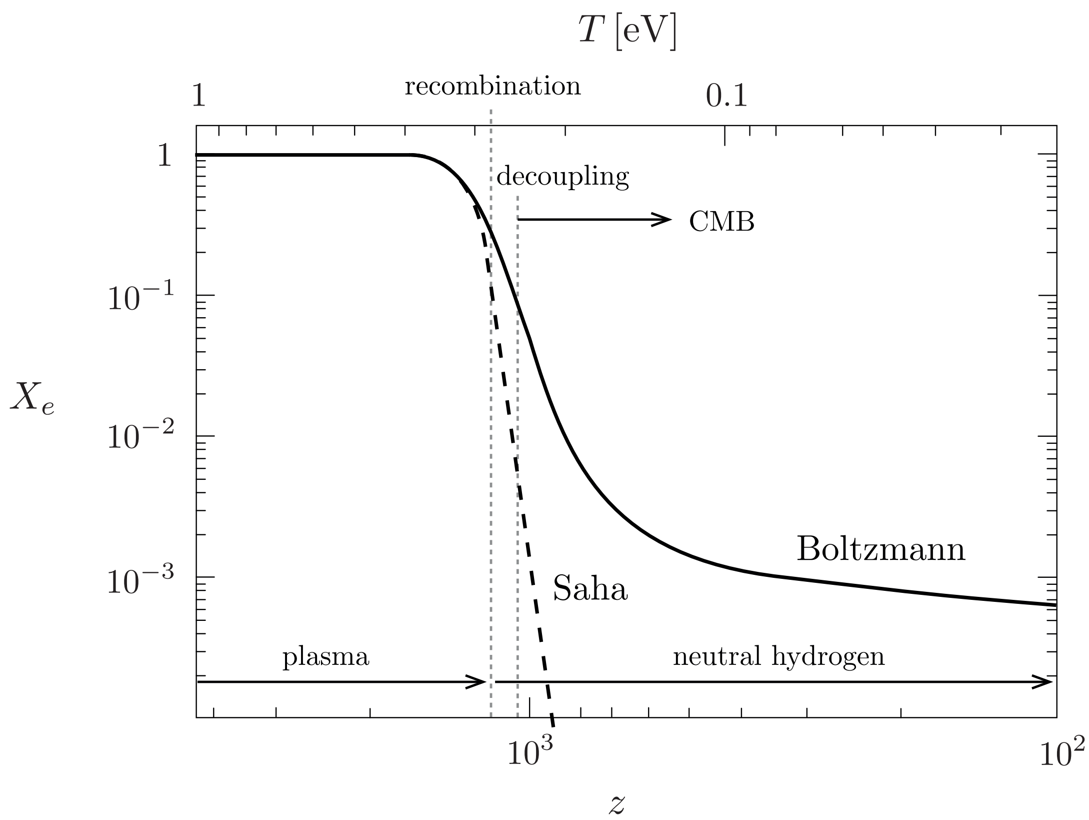
  - fraction of free electrons (Saha equation):

$$\frac{1-X_e}{X_e^2} = \frac{2\zeta(3)}{\pi^2}\eta\left(\frac{2\pi kT}{c^2 m_e}\right)^{3/2} e^{B_H/kT}$$

- CMBR origin calculation – hydrogen recombination

  - fraction of free electrons (Saha equation):

$$\frac{1-X_e}{X_e^2} = \frac{2\zeta(3)}{\pi^2}\eta\left(\frac{2\pi kT}{c^2 m_e}\right)^{3/2} e^{B_H/kT}$$



- CMBR origin calculation – hydrogen recombination

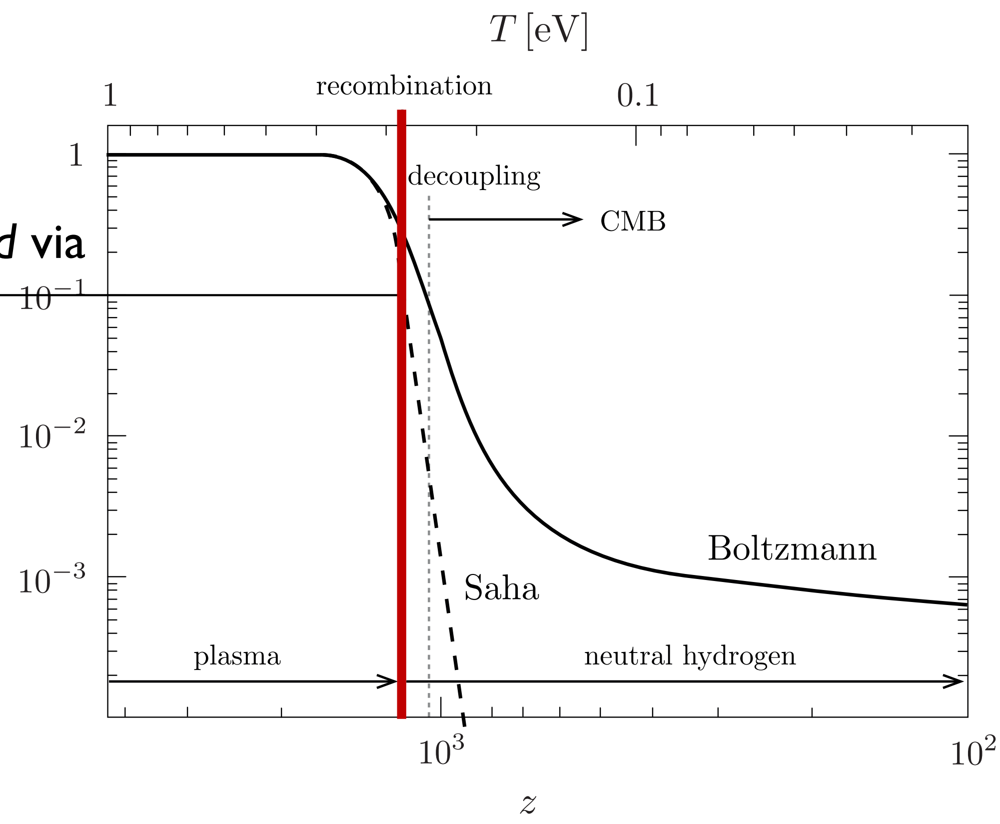
  - fraction of free electrons (Saha equation):

$$\frac{1-X_e}{X_e^2} = \frac{2\zeta(3)}{\pi^2}\eta\left(\frac{2\pi kT}{c^2 m_e}\right)^{3/2} e^{B_H/kT}$$

recombination *defined* via

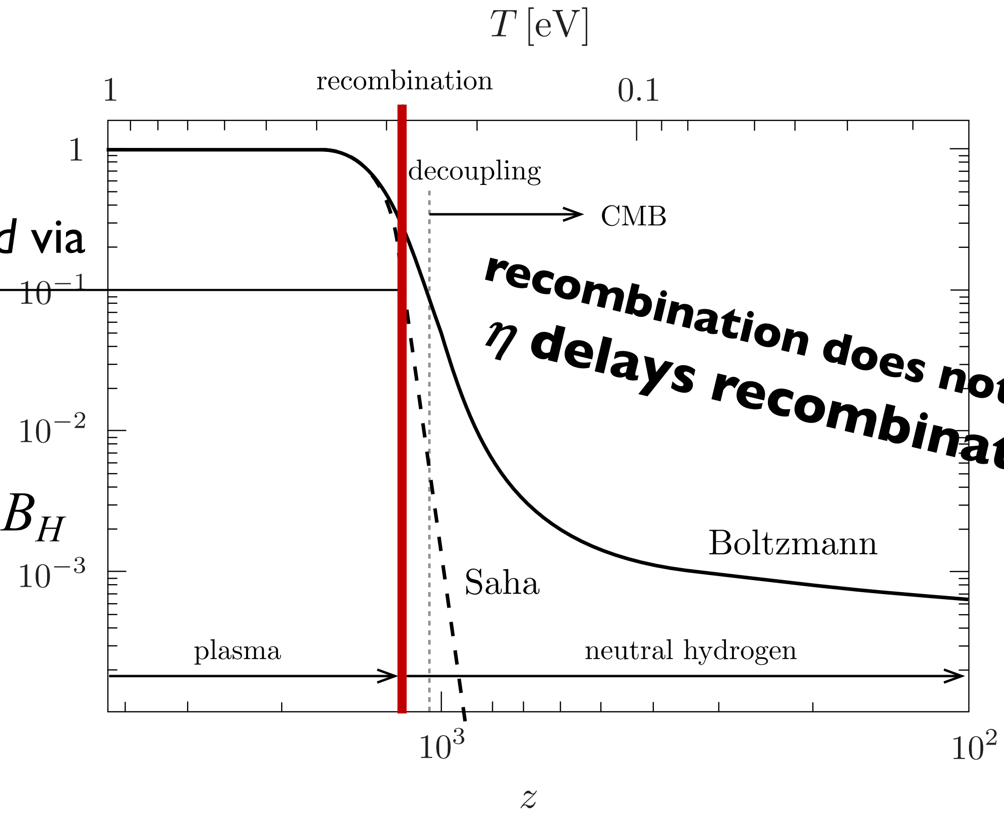
X_e=0.1

T_{rec}= 0.31eV



- CMBR origin calculation – hydrogen recombination
    - fraction of free electrons (Saha equation):

$$\frac{1-X_e}{X_e^2} = \frac{2\zeta(3)}{\pi^2}\eta\left(\frac{2\pi kT}{c^2 m_e}\right)^{3/2} e^{B_H/kT}$$



recombination *defined* via

X_e=0.1

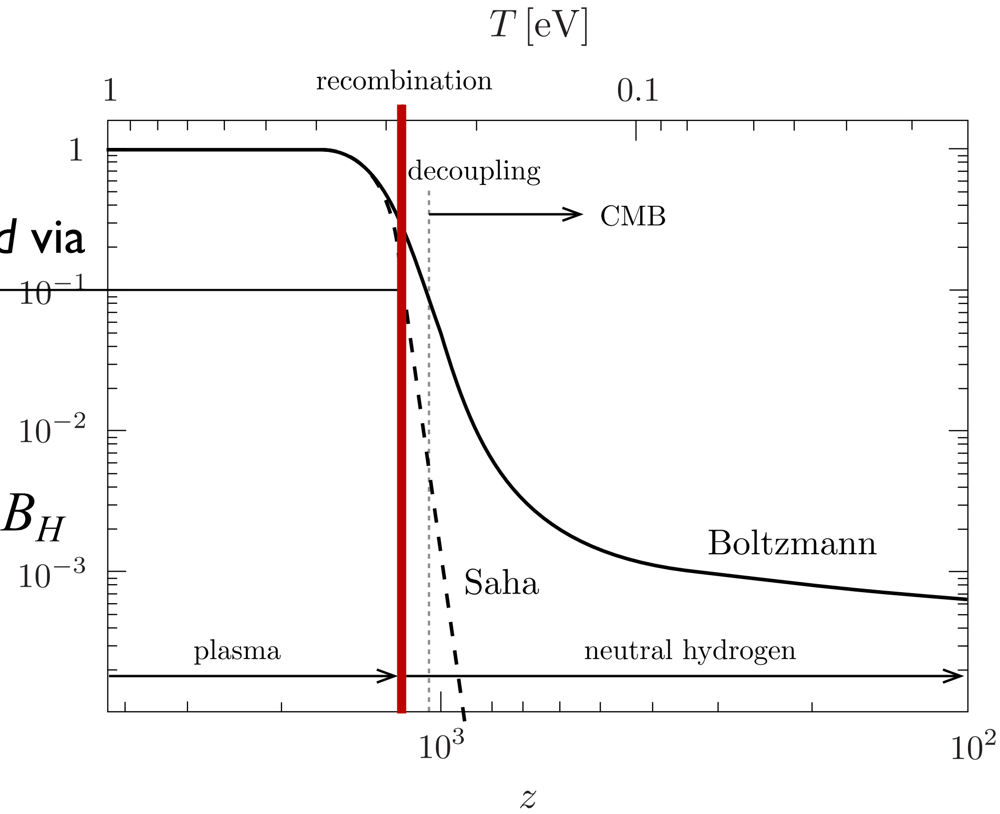
T_{rec}= 0.31eV << B_H

recombination does not happen at T=13.6eV:
η delays recombination considerably!

▪ CMBR origin calculation – hydrogen recombination

• fraction of free electrons (Saha equation):

$$\frac{1-X_e}{X_e^2} = \frac{2\zeta(3)}{\pi^2}\eta\left(\frac{2\pi kT}{c^2 m_e}\right)^{3/2} e^{B_H/kT}$$



recombination *defined* via

X_e=0.1

↓

T_{rec}= 0.31eV << B_H

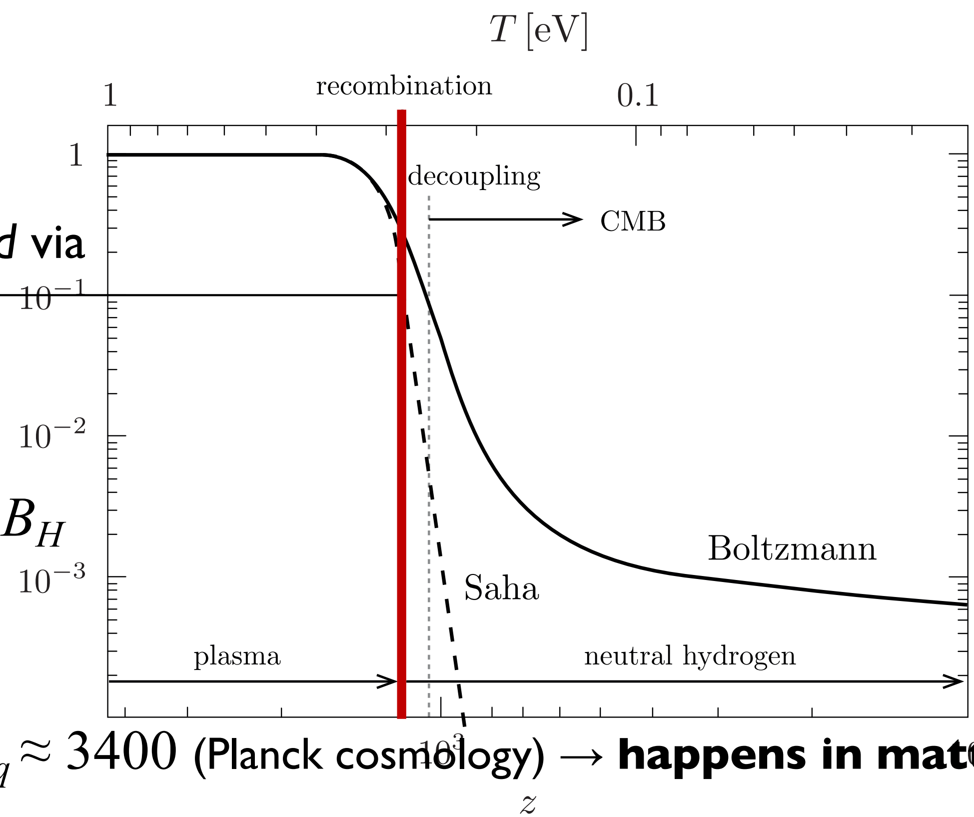
↓

z_{rec}= 1330

- CMBR origin calculation – hydrogen recombination

  - fraction of free electrons (Saha equation):

$$\frac{1-X_e}{X_e^2} = \frac{2\zeta(3)}{\pi^2}\eta\left(\frac{2\pi kT}{c^2 m_e}\right)^{3/2} e^{B_H/kT}$$



recombination *defined* via

$X_e = 0.1$ ←

↓

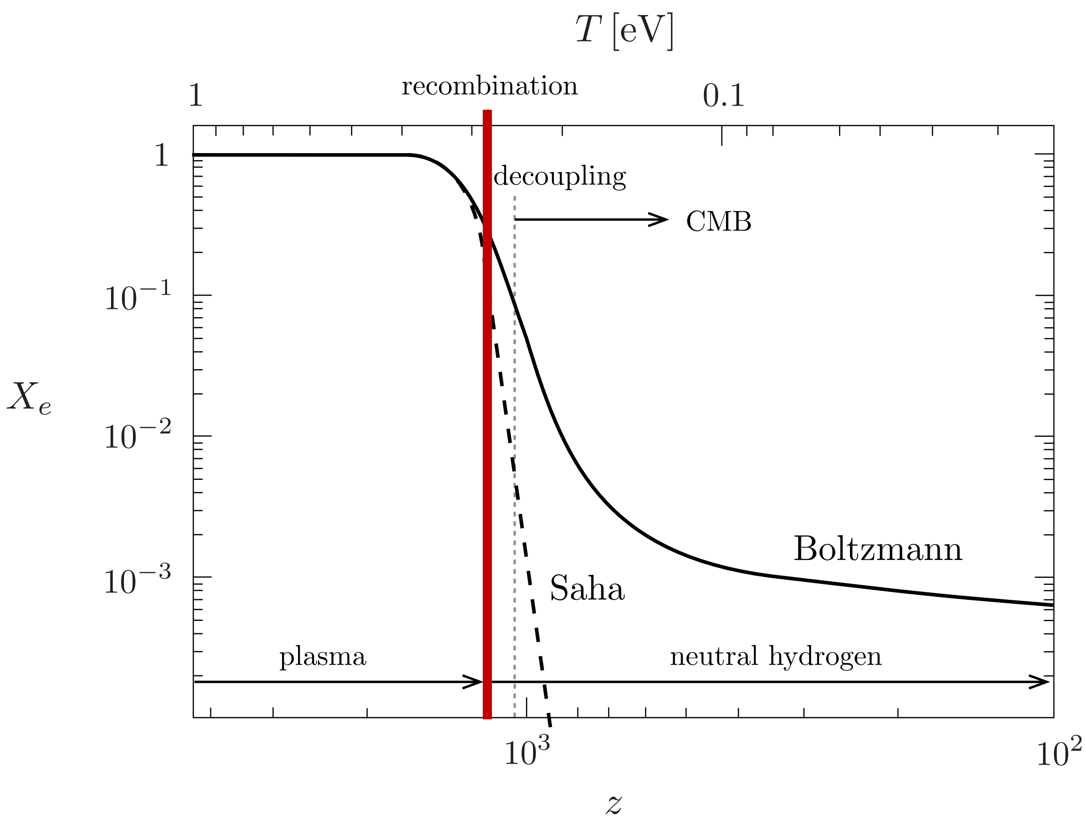
$T_{rec} = 0.31 \text{eV} << B_H$

↓

$z_{rec} = 1330 << z_{eq} \approx 3400$ (Planck cosmology) → **happens in matter domination**

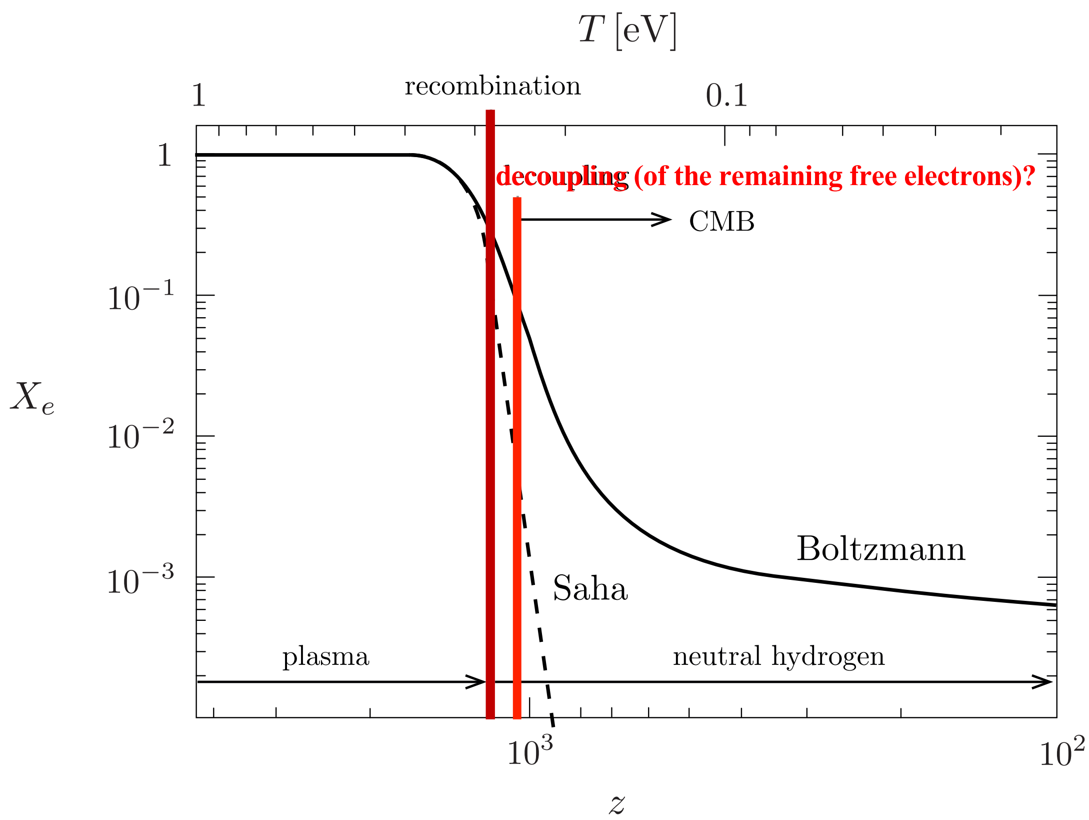
- CMBR origin calculation – hydrogen recombination

  - hydrogen recombination: $T_{\rm rec} = 0.31\,{\rm eV}$
    $z_{\rm rec} = 1330$ (*defined* via X_e=0.1 and hence not instantaneous!)



- CMBR origin calculation – hydrogen recombination

  - hydrogen recombination: $T_{\text{rec}} = 0.31\text{eV}$
    $z_{\text{rec}} = 1330$ (*defined* via X_e=0.1 and hence not instantaneous!)



- CMBR origin calculation – photon decoupling

  - hydrogen recombination: $T_{\mathrm{rec}} = 0.31\mathrm{eV}$
    $z_{\mathrm{rec}} = 1330$

  - photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

    decoupling condition: $\Gamma / H < 1$

▪ CMBR origin calculation – photon decoupling

- hydrogen recombination: $T_{\mathrm{rec}} = 0.31\,\mathrm{eV}$
  $z_{\mathrm{rec}} = 1330$

- photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

  decoupling condition: $\Gamma / H < 1$

$$\Gamma_\gamma \approx n_e \, \sigma_T c$$

- CMBR origin calculation – photon decoupling

  - hydrogen recombination: $T_{\mathrm{rec}} = 0.31\mathrm{eV}$
    $z_{\mathrm{rec}} = 1330$

  - photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

    decoupling condition: $\Gamma/H < 1$

$$\Gamma_\gamma \approx n_e\, \sigma_T c = n_b X_e\, \sigma_T c$$

▪ CMBR origin calculation – photon decoupling

- hydrogen recombination: $T_{\mathrm{rec}} = 0.31\mathrm{eV}$
  $z_{\mathrm{rec}} = 1330$

- photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

  decoupling condition: $\Gamma/H < 1$

$$\Gamma_\gamma \approx n_e\, \sigma_T c = n_b X_e\, \sigma_T c = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3\, X_e \sigma_T c$$

- CMBR origin calculation – photon decoupling

  - hydrogen recombination: $T_{\text{rec}} = 0.31\text{eV}$
    $z_{\text{rec}} = 1330$

  - photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

    decoupling condition: $\Gamma / H < 1$

$$\Gamma_\gamma \approx n_e\ \sigma_T c = n_b X_e\ \sigma_T c = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3\ X_e \sigma_T c$$

$$H = \ldots$$

▪ CMBR origin calculation – photon decoupling

- hydrogen recombination: $T_{\mathrm{rec}} = 0.31\,\mathrm{eV}$
  $z_{\mathrm{rec}} = 1330$

- photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

  decoupling condition: $\Gamma / H < 1$

$$\Gamma_\gamma \approx n_e\,\sigma_T c = n_b X_e\,\sigma_T c = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3\,X_e \sigma_T c$$

$$H = \left(H_0^2 \Omega_{m,0} R^{-3}\right)^{1/2}$$ matter domination (as $z_{\mathrm{rec}} << z_{\mathrm{eq}}$):

- CMBR origin calculation – photon decoupling

  - hydrogen recombination: $T_{\mathrm{rec}} = 0.31\mathrm{eV}$
    $z_{\mathrm{rec}} = 1330$

  - photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

    decoupling condition: $\Gamma / H < 1$

$$\Gamma_\gamma \approx n_e\, \sigma_T c = n_b X_e\, \sigma_T c = \eta \frac{2\zeta(3)}{\pi^2} \left(\frac{k}{\hbar c} \right)^3 T^3\, X_e \sigma_T c$$

$H = \left(H_0^2 \Omega_{m,0} R^{-3} \right)^{1/2}$ matter domination (as $z_{\mathrm{rec}} << z_{\mathrm{eq}}$):

$T \propto R^{-1}$ for photons

- CMBR origin calculation – photon decoupling

  - hydrogen recombination: $T_{\text{rec}} = 0.31\text{eV}$
    $z_{\text{rec}} = 1330$

  - photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

    decoupling condition: $\Gamma/H < 1$

$$\Gamma_\gamma \approx n_e\ \sigma_T c = n_b X_e\ \sigma_T c = \eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T^3\ X_e \sigma_T c$$

$$H = H_0 \sqrt{\Omega_{m,0}}\left(\frac{T}{T_0}\right)^{3/2}$$

(T is the temperature of the photons!)

- CMBR origin calculation – photon decoupling

  - hydrogen recombination: $T_{\mathrm{rec}} = 0.31\mathrm{eV}$
    $z_{\mathrm{rec}} = 1330$

  - photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

    decoupling condition: $\Gamma / H < 1$

$$\underbrace{\eta \frac{2\zeta(3)}{\pi^2} \left(\frac{k}{\hbar c}\right)^3 T_{dec}^3 X_e \sigma_T c}_{\Gamma} \approx \underbrace{H_0 \sqrt{\Omega_{m,0}} \left(\frac{T_{dec}}{T_0}\right)^{3/2}}_{H}$$

▪ CMBR origin calculation – photon decoupling

- hydrogen recombination: $T_{\rm rec} = 0.31\,\mathrm{eV}$
  $z_{\rm rec} = 1330$

- photon decoupling: $e^- + \gamma \leftrightarrow e^- + \gamma$

  decoupling condition: $\Gamma/H < 1$

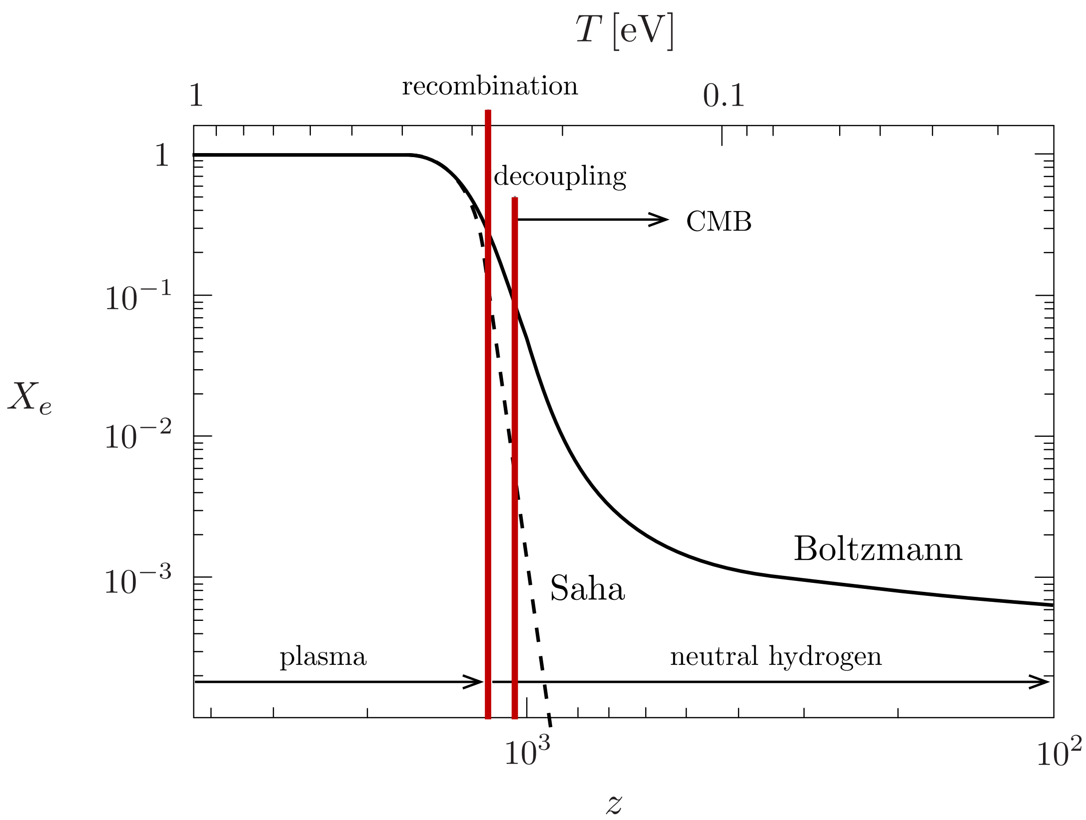
$$\eta \frac{2\zeta(3)}{\pi^2}\left(\frac{k}{\hbar c}\right)^3 T_{dec}^3 X_e \sigma_T c \approx H_0 \sqrt{\Omega_{m,0}}\left(\frac{T_{dec}}{T_0}\right)^{3/2}$$

- use Saha equation for $X_e(T_{dec})$
- solve for T_{dec}

▪ CMBR origin calculation – photon decoupling

- hydrogen recombination: $T_{rec} = 0.31\text{eV}$
  $z_{rec} = 1330$

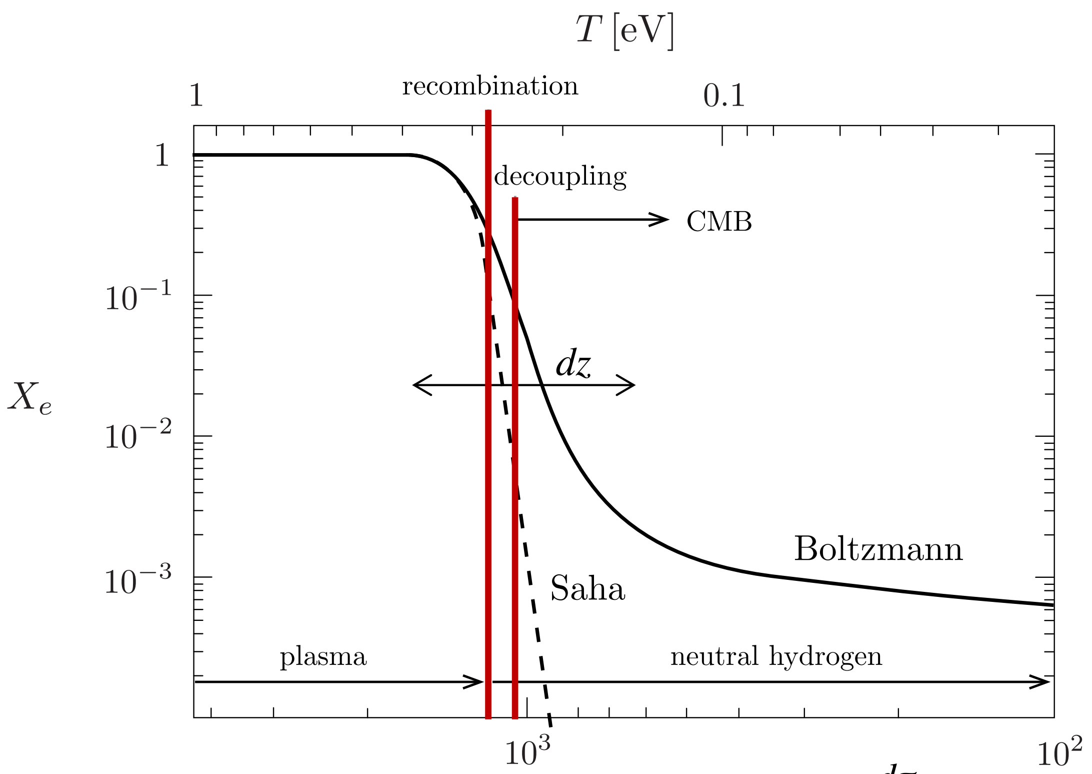
- photon decoupling: $T_{dec} = 0.27\text{eV}$
  $z_{dec} = 1090$



- CMBR origin calculation – photon decoupling

  - hydrogen recombination: $T_{\text{rec}} = 0.31\text{eV}$, $z_{\text{rec}} = 1330$

  - photon decoupling: $T_{\text{dec}} = 0.27\text{eV}$, $z_{\text{dec}} = 1090$



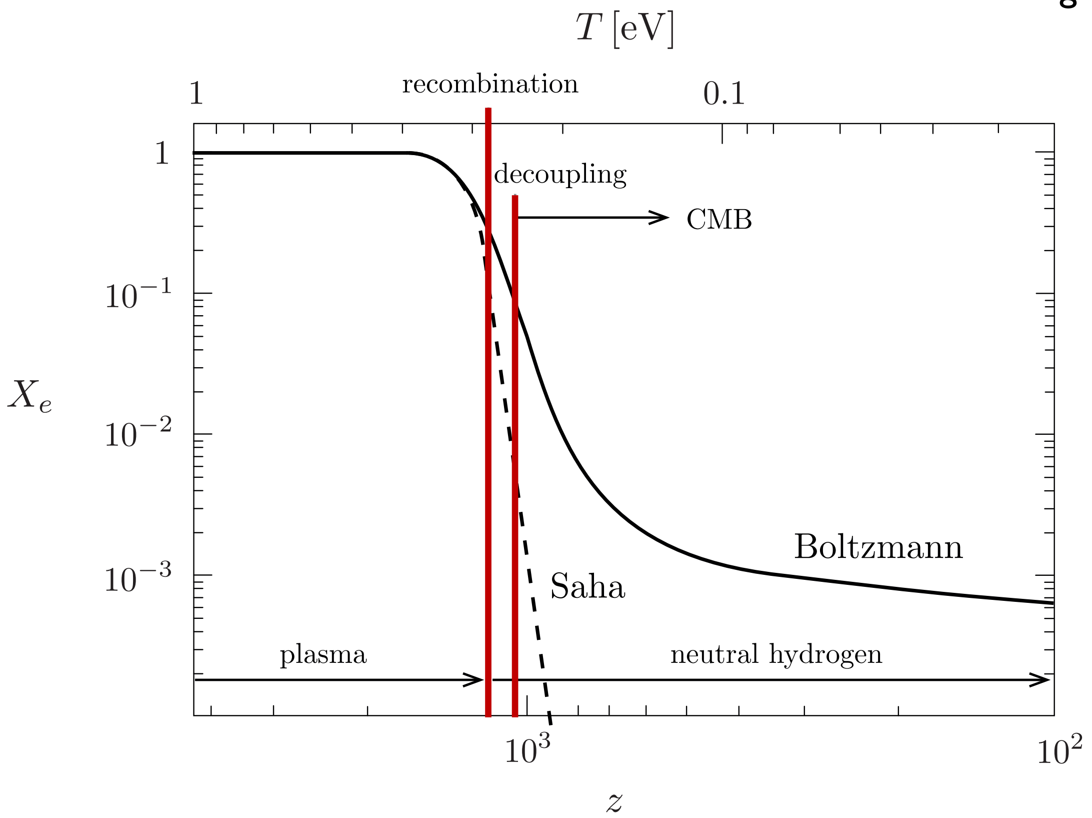
redshift interval: scattering probability in [z, $z+dz$]: $p(z)dz = e^{-\tau}\dfrac{d\tau}{dz}dz$ (τ: optical depth)

▪ CMBR origin calculation – photon decoupling

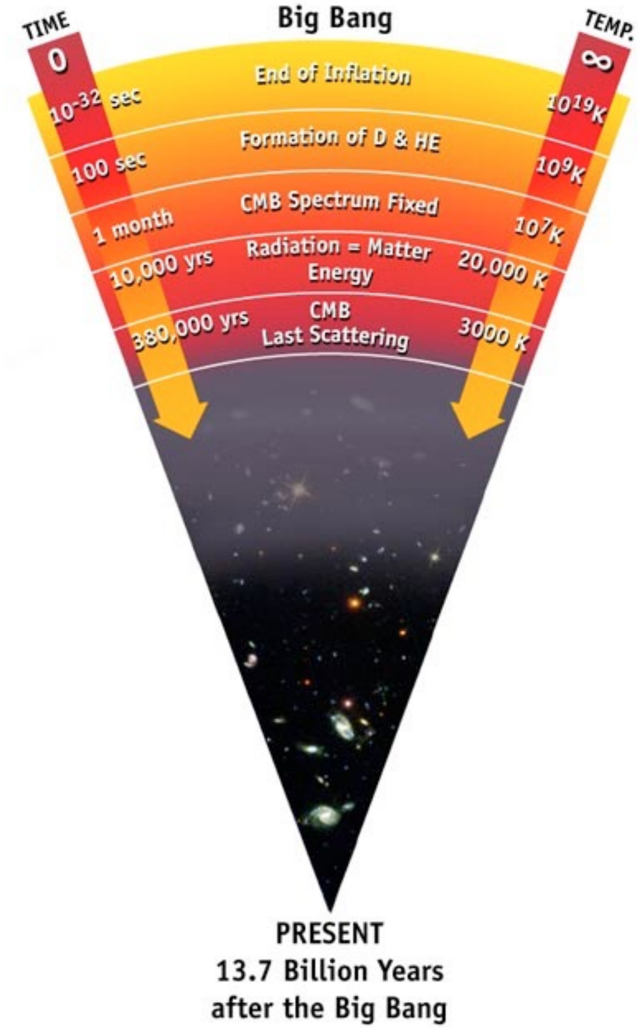
- hydrogen recombination: $T_{rec} = 0.31\text{eV}$
  $z_{rec} = 1330$

- photon decoupling: $T_{dec} = 0.27\text{eV}$
  $z_{dec} = 1090$

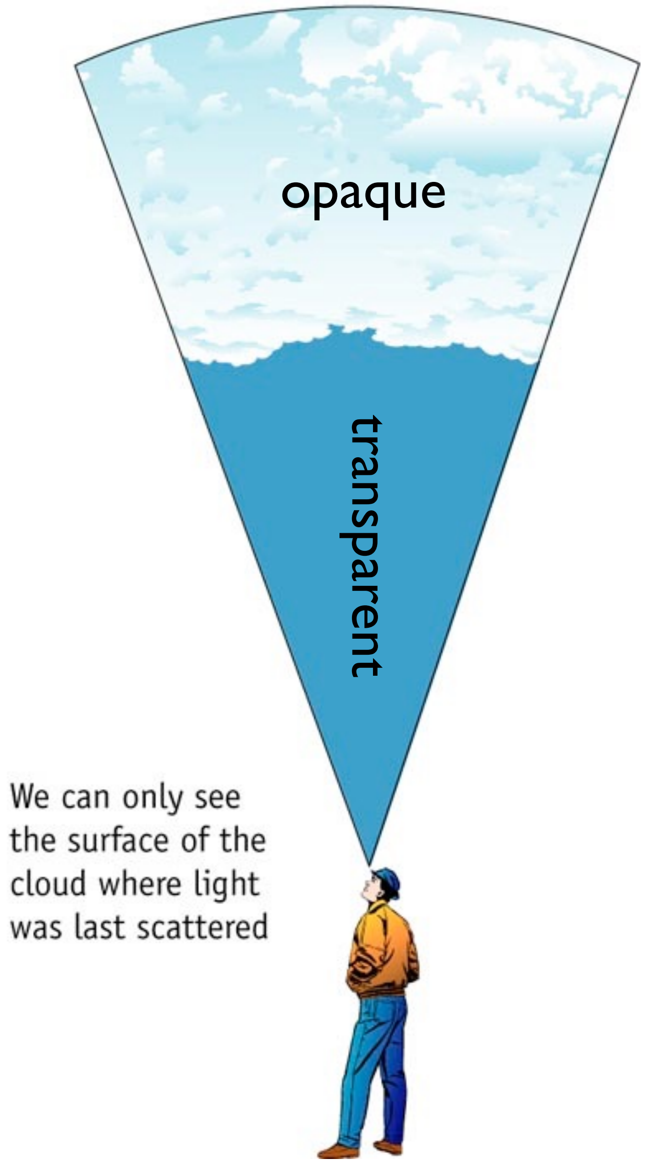
defines last scattering surface



- last scattering surface



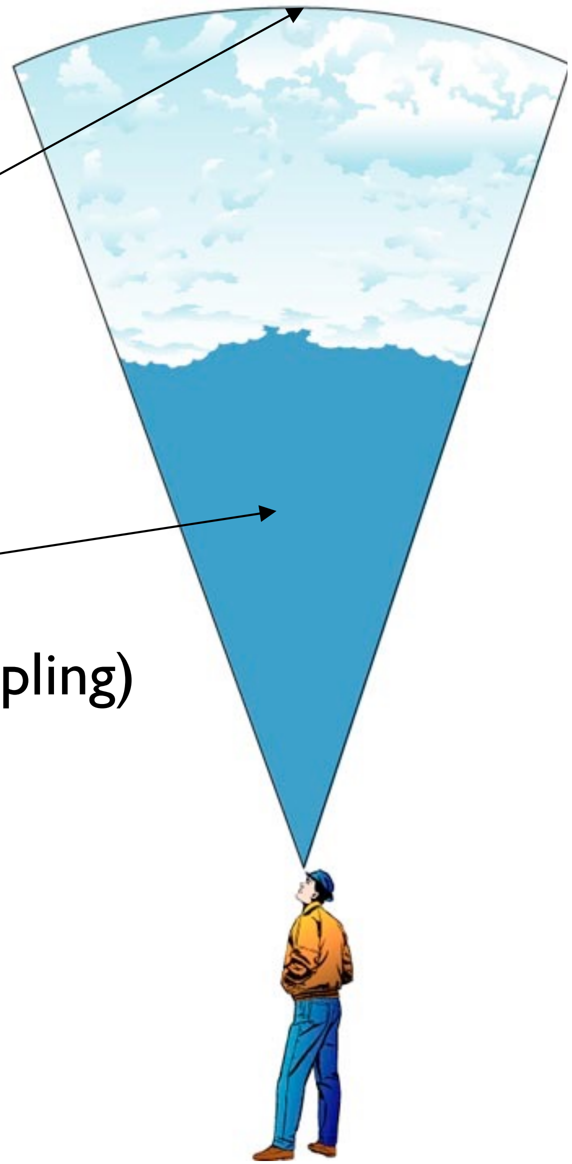
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



- discovery
- origin
- **CMB fluctuations**
  - primary
  - secondary

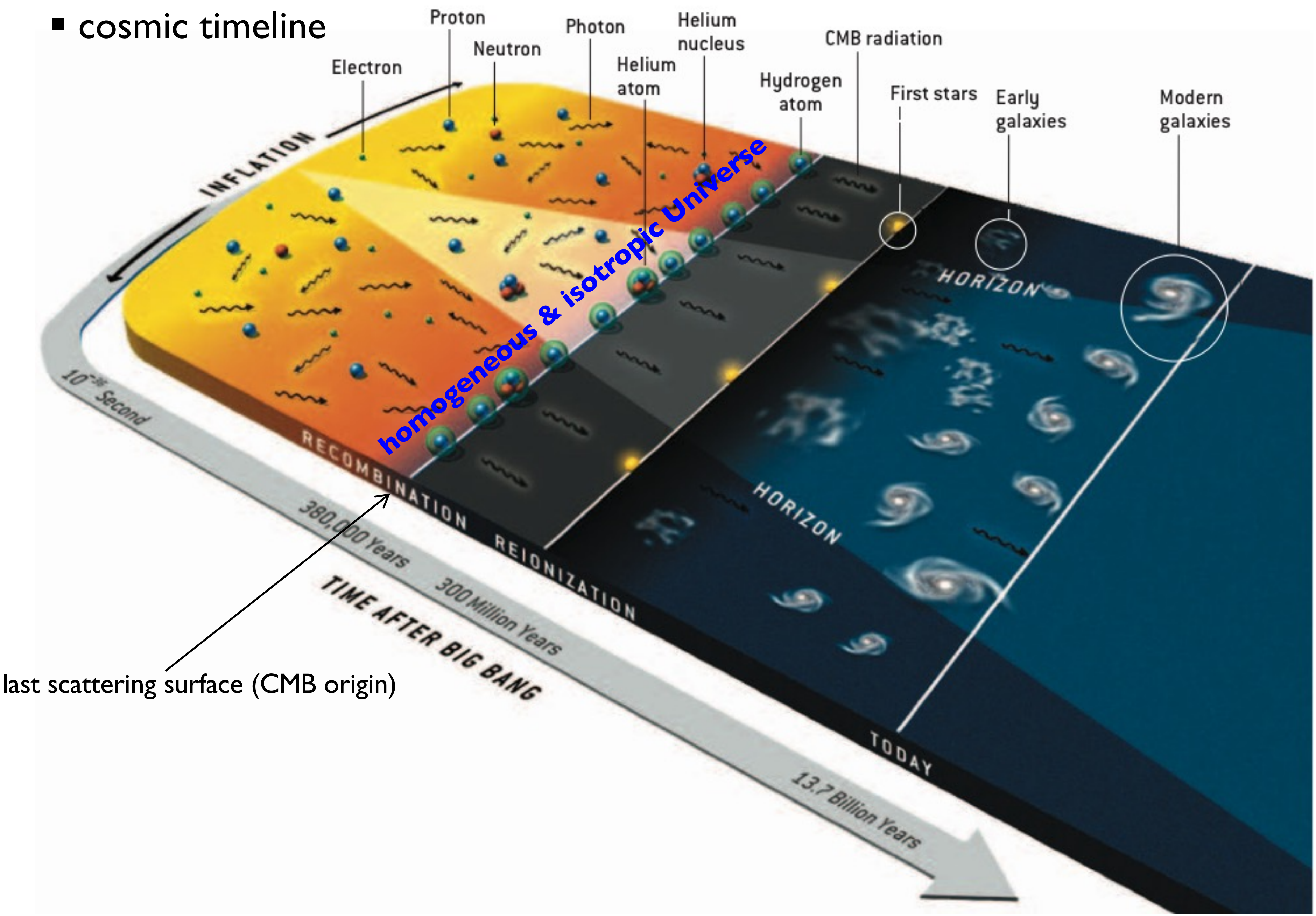
- discovery
- origin
- **CMB fluctuations**
  - primary (created during inflation)
  - secondary (created after photon decoupling)

- discovery
- origin
- **CMB fluctuations**
  - primary (created during inflation)
  - secondary (created after photon decoupling)

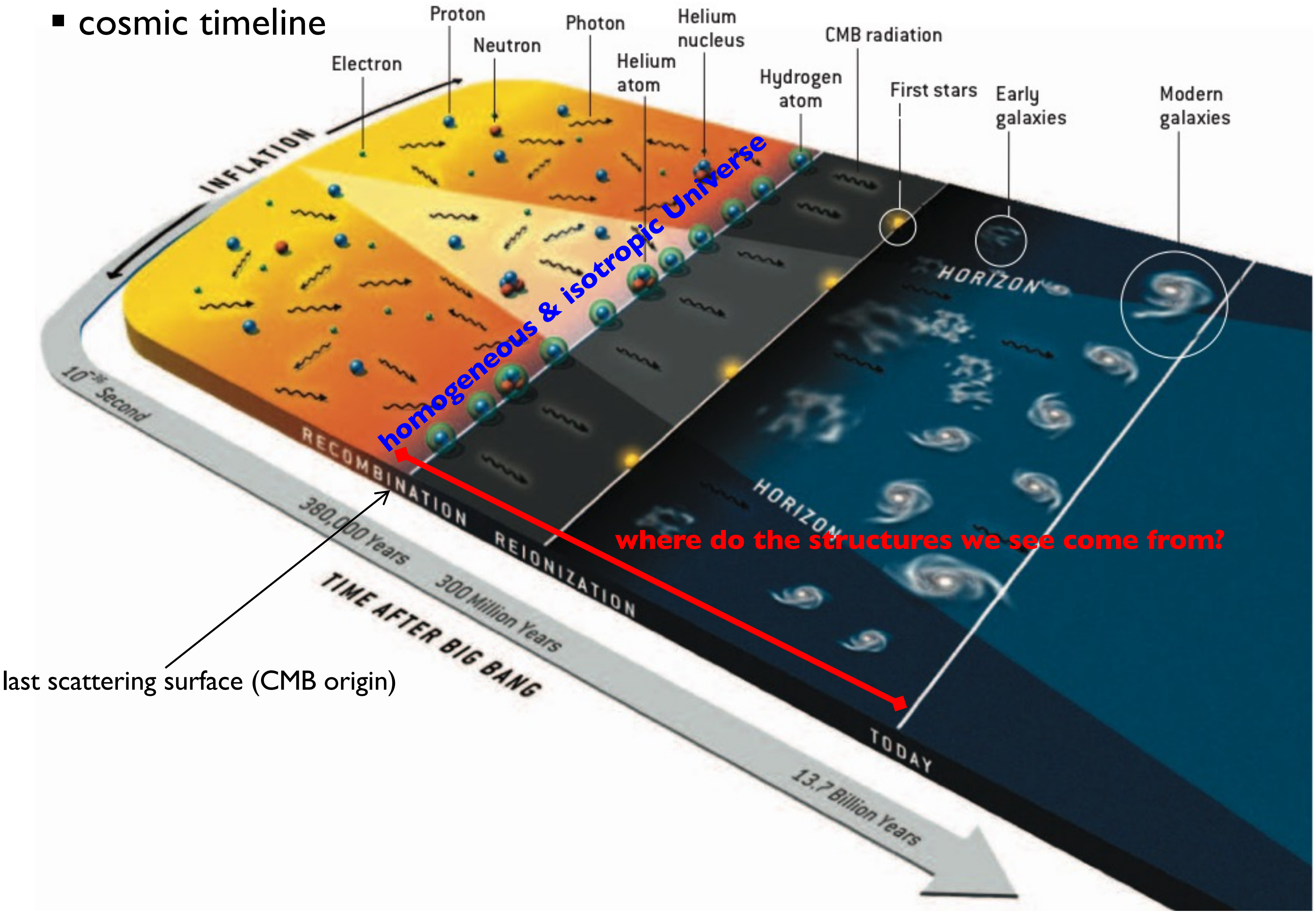


- discovery
- origin
- **CMB fluctuations**
  - primary (created during inflation):
    - **intrinsic fluctuations**
    - how to quantify them?
    - what's their nature?
    - sensitivity to cosmological parameters?
  - secondary (created after photon decoupling):
    - what's their nature?
    - what's their importance?

- cosmic timeline

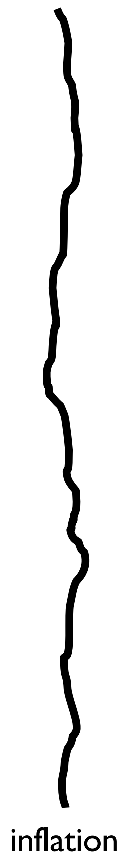


- cosmic timeline

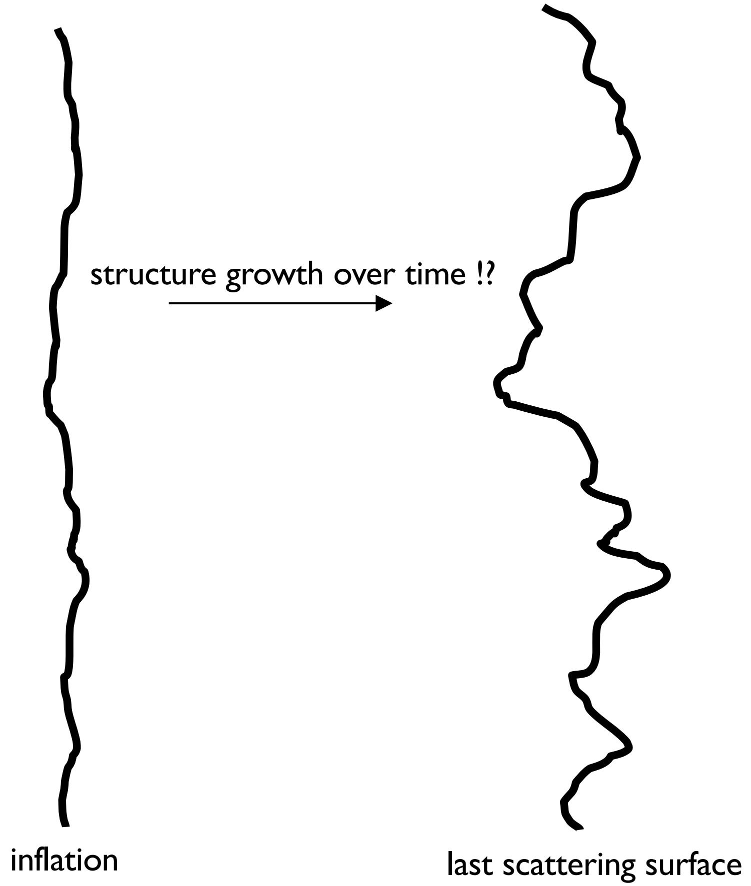


there must be some primordial matter(!) fluctuations
acting as seeds for all the structures in the Universe!?

- seed inhomogeneities and their relation to temperature fluctuations:
    - "inflation" of quantum fluctuations

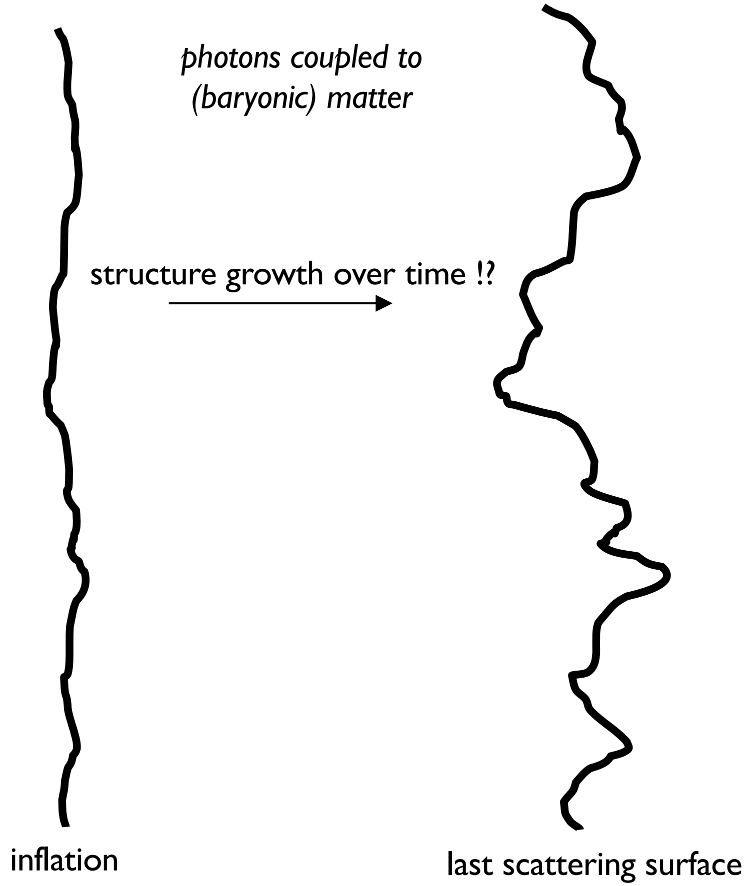


- seed inhomogeneities and their relation to temperature fluctuations:
    - "inflation" of quantum fluctuations lead to...
    - primordial matter perturbations*

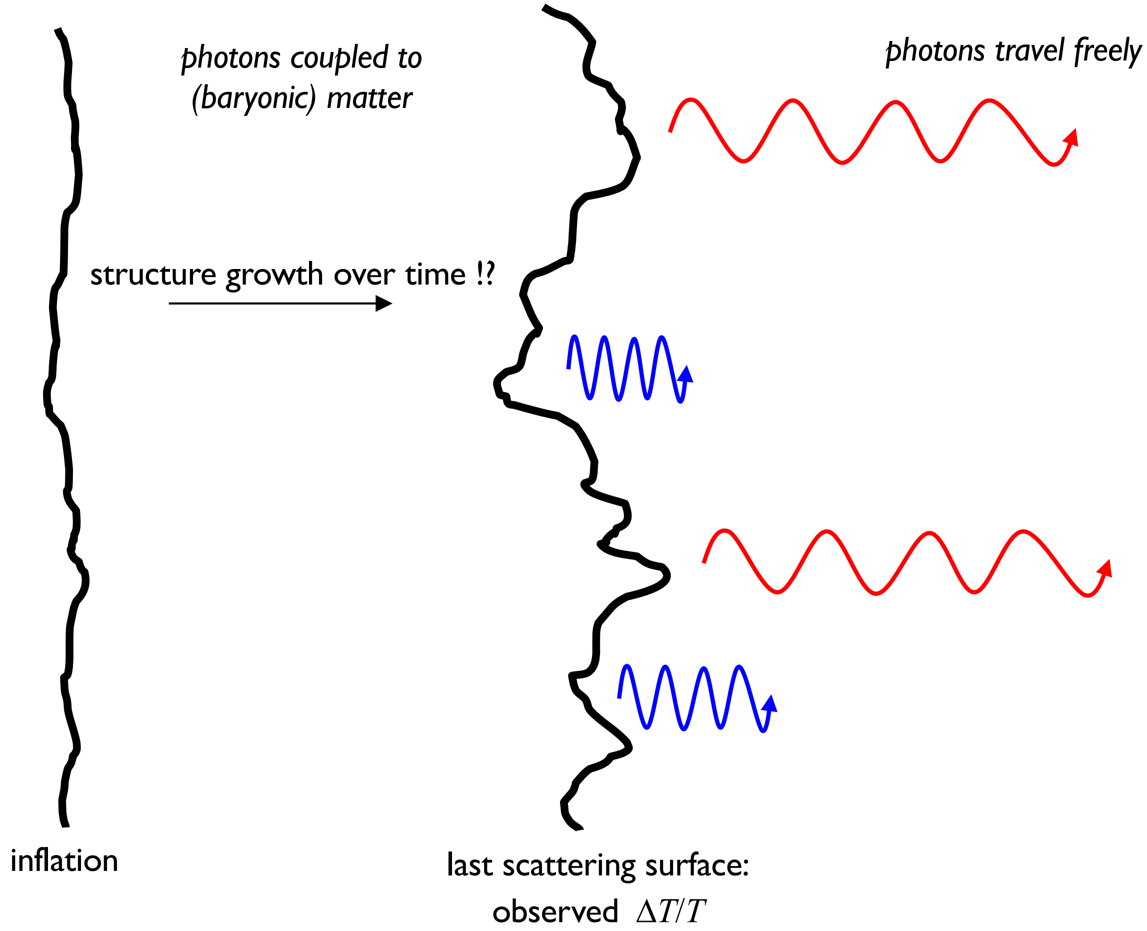


*Note: we are not dealing with dark matter perturbations here as they decoupled after inflation, but long before 'last scattering'

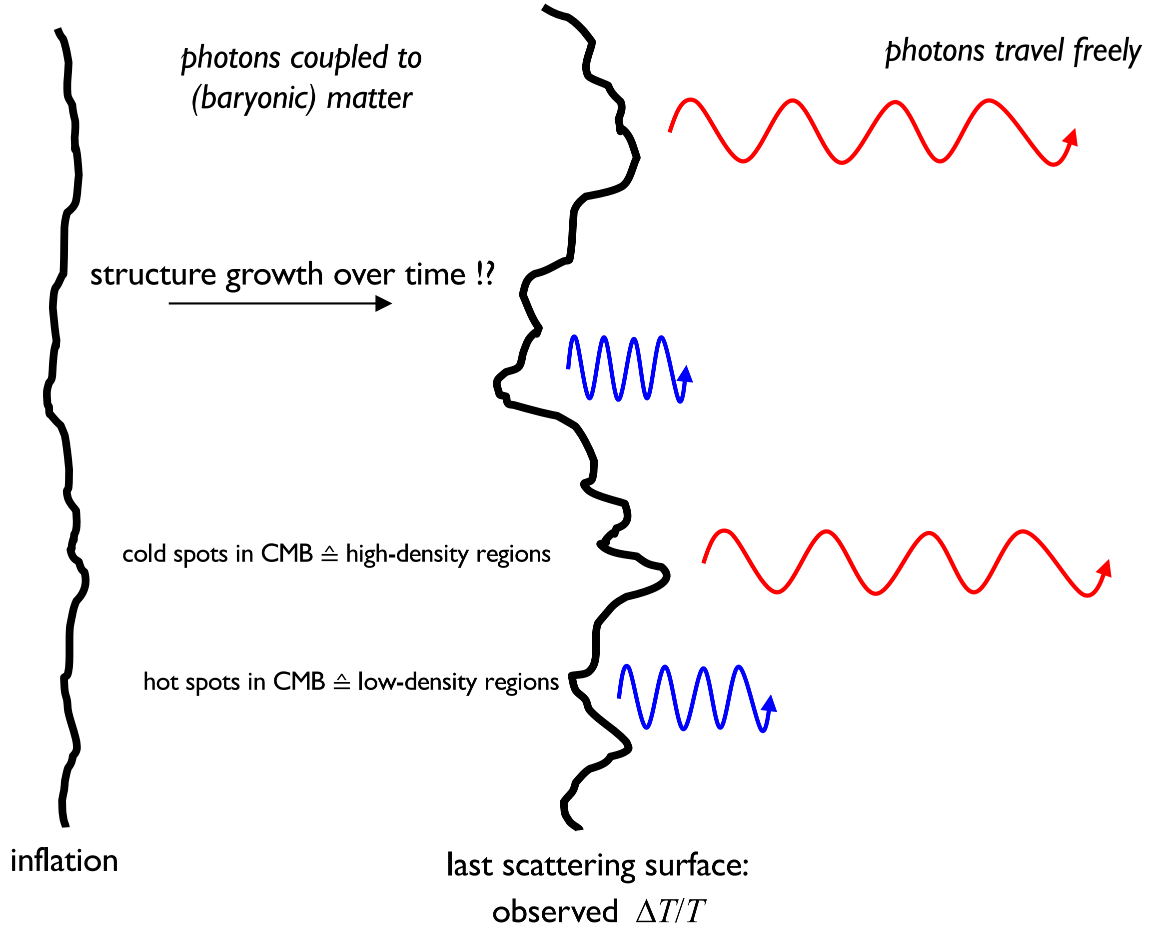
- seed inhomogeneities and their relation to temperature fluctuations:
  - "inflation" of quantum fluctuations lead to...
  - primordial matter perturbations



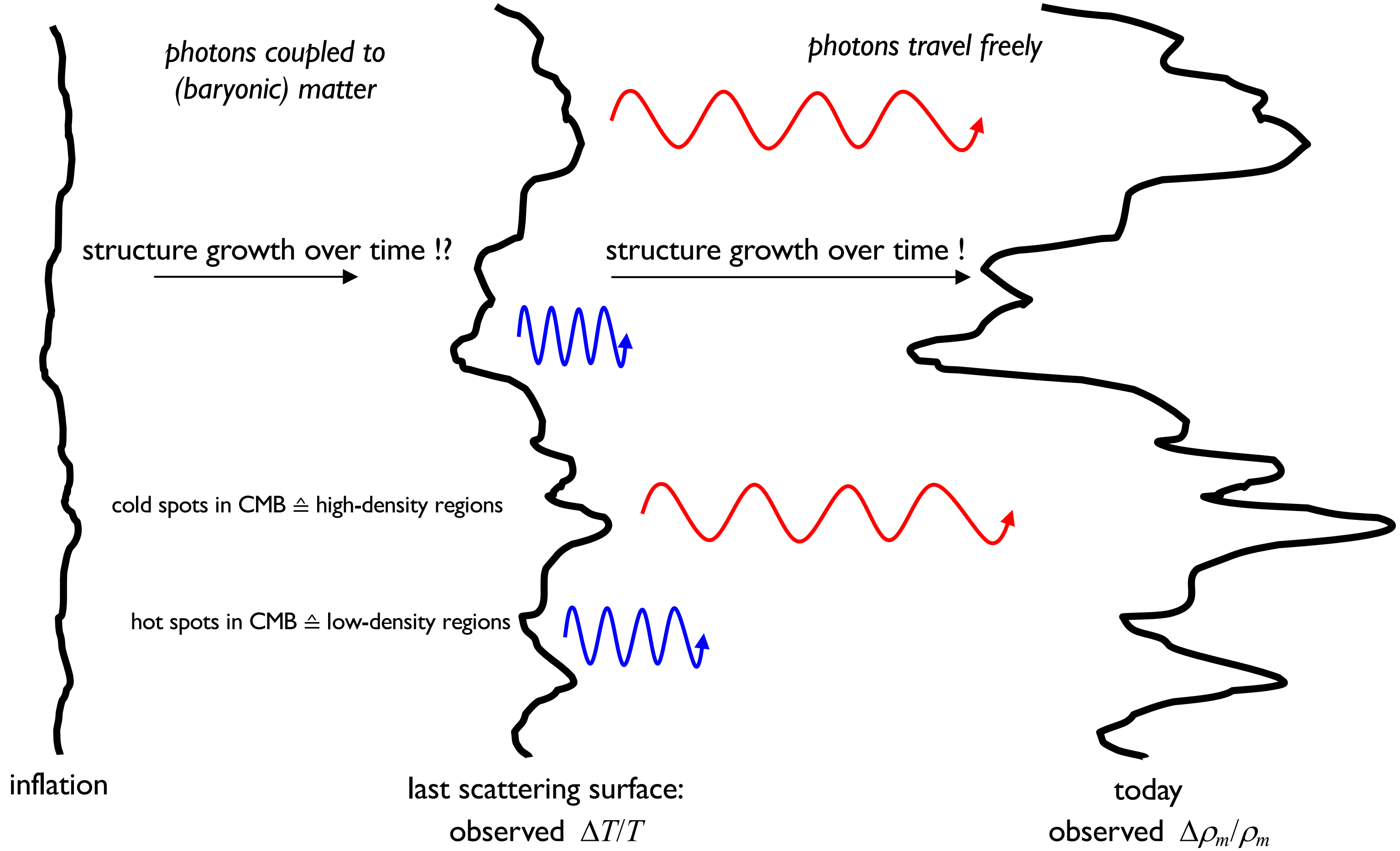
- seed inhomogeneities and their relation to temperature fluctuations:
  - primordial matter perturbations lead to…
  - …intrinsic fluctuations in the CMB



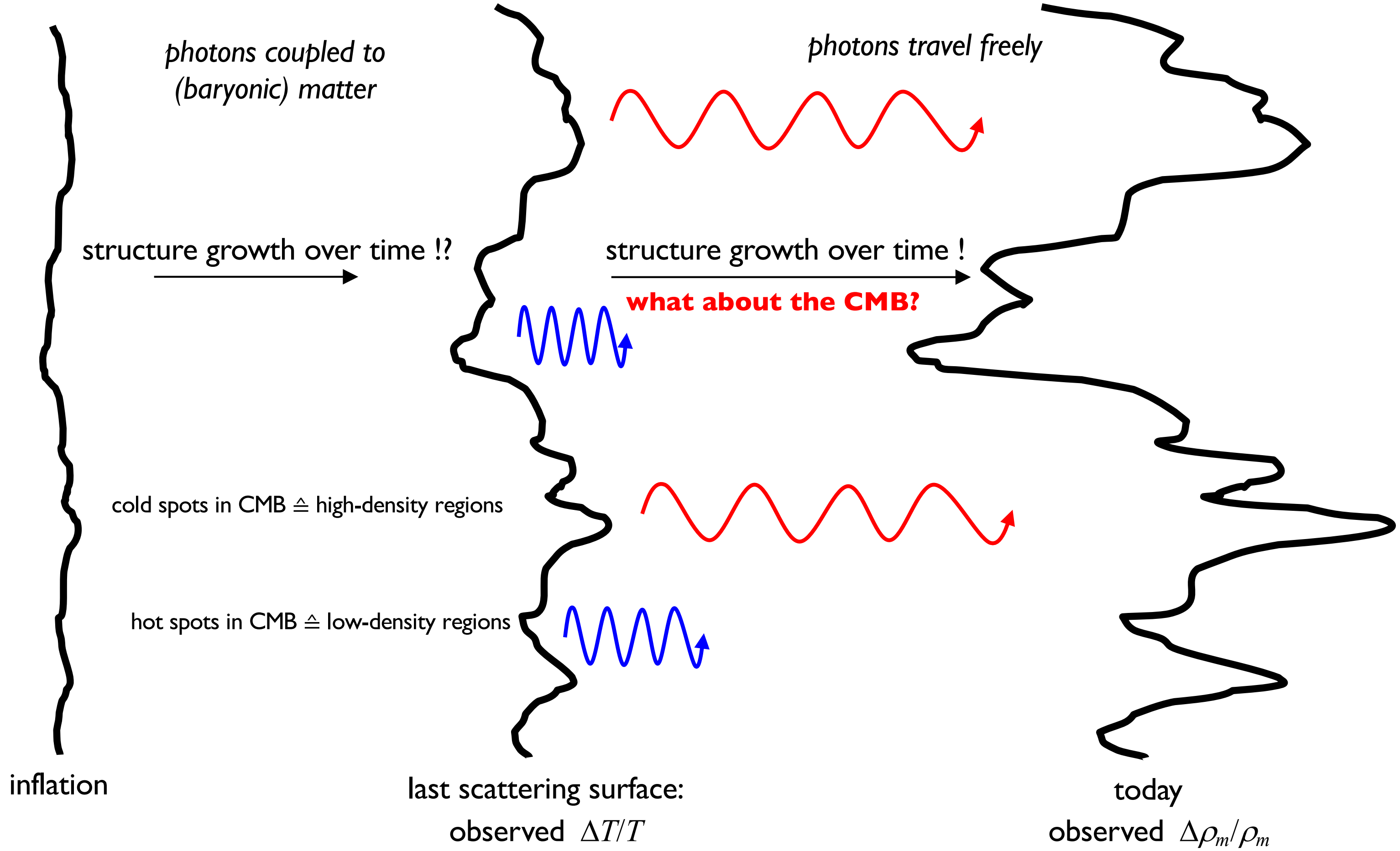
- seed inhomogeneities and their relation to temperature fluctuations:
  - primordial matter perturbations lead to…
  - …intrinsic fluctuations in the CMB



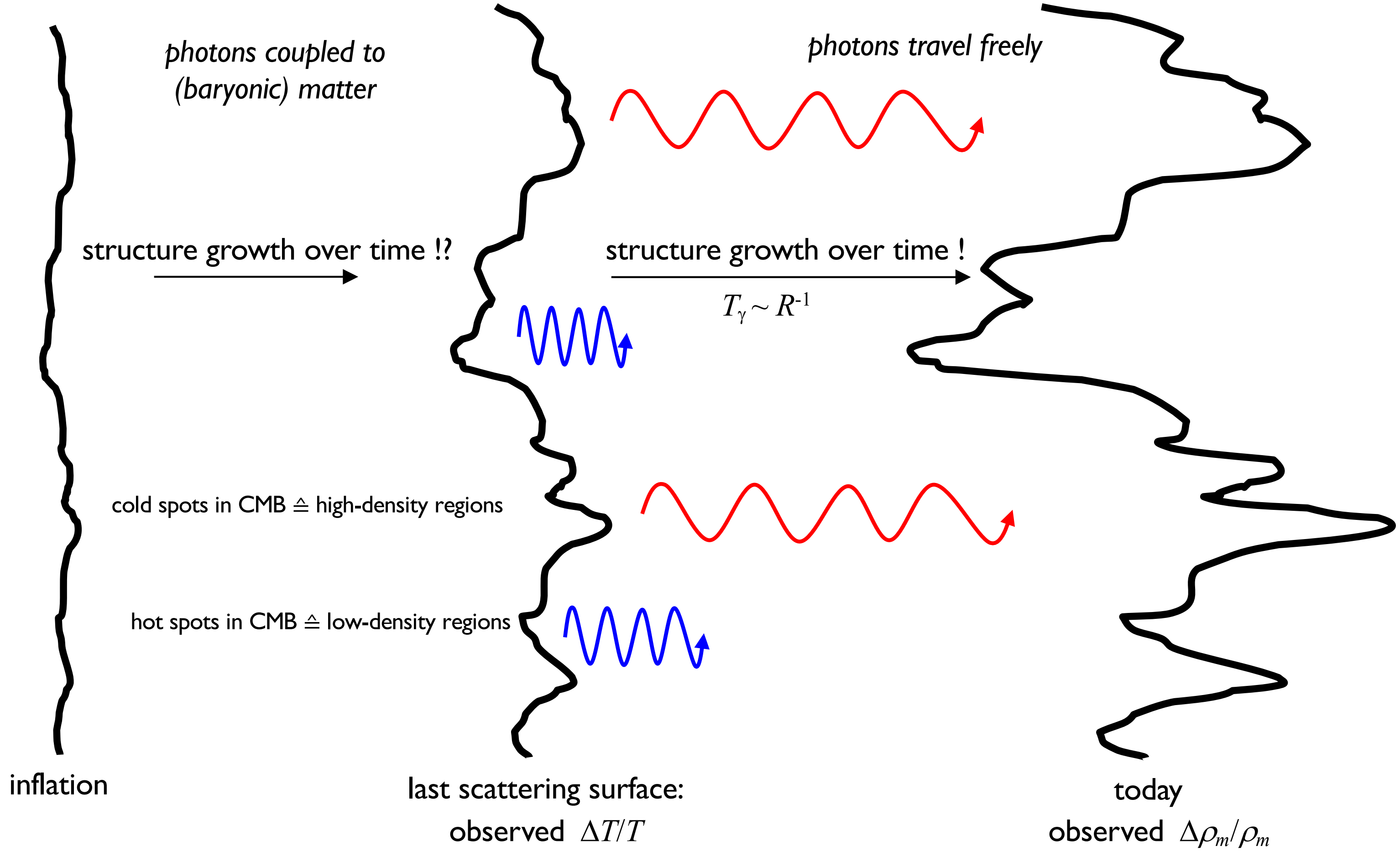
- seed inhomogeneities and their relation to temperature fluctuations:
    - primordial matter perturbations are amplified via gravity
    - …intrinsic fluctuations in the CMB



- seed inhomogeneities and their relation to temperature fluctuations:
  - primordial matter perturbations are amplified via gravity
  - …intrinsic fluctuations in the CMB

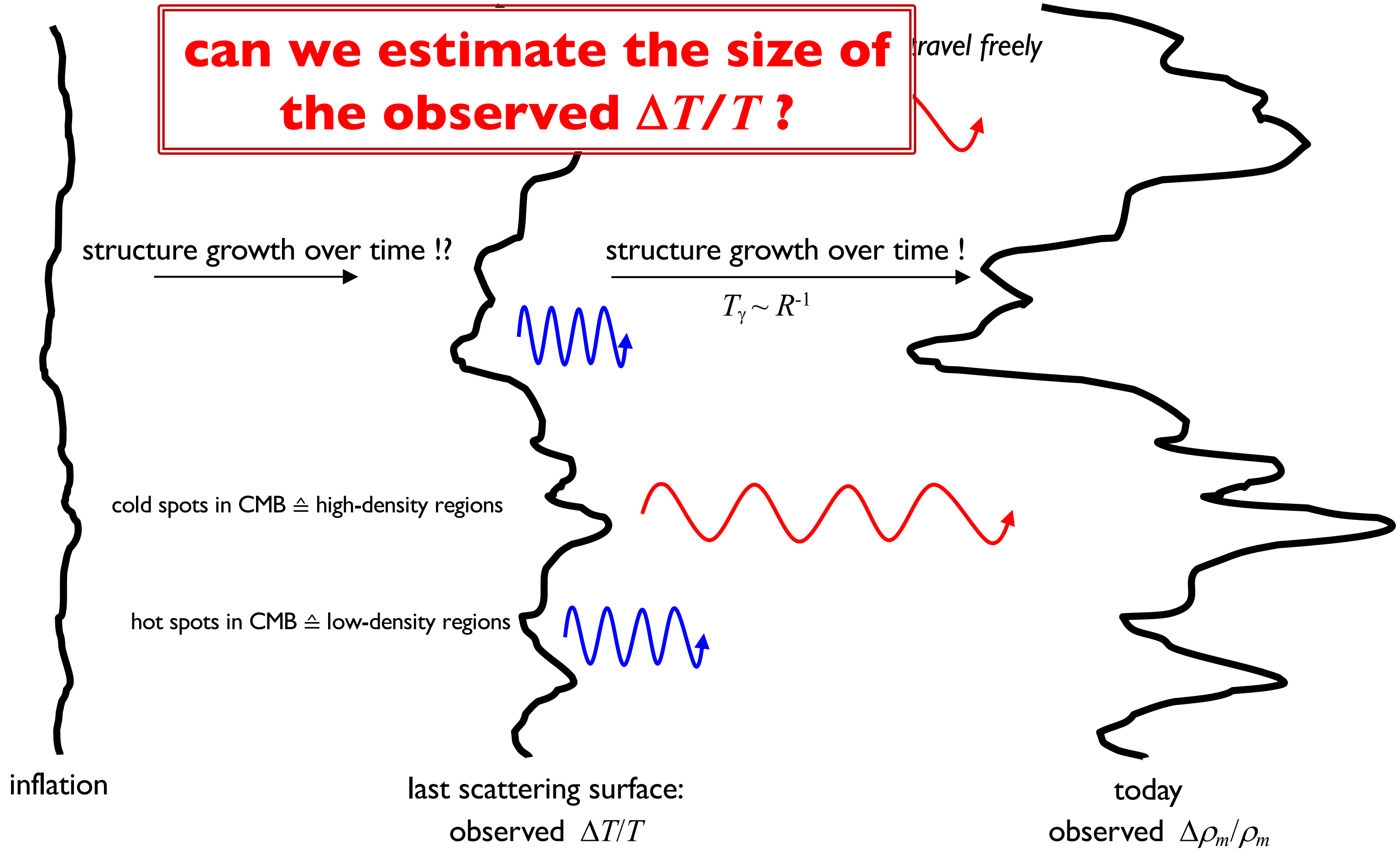


- seed inhomogeneities and their relation to temperature fluctuations:
  - primordial matter perturbations are amplified via gravity
  - intrinsic fluctuations in CMB are conserved

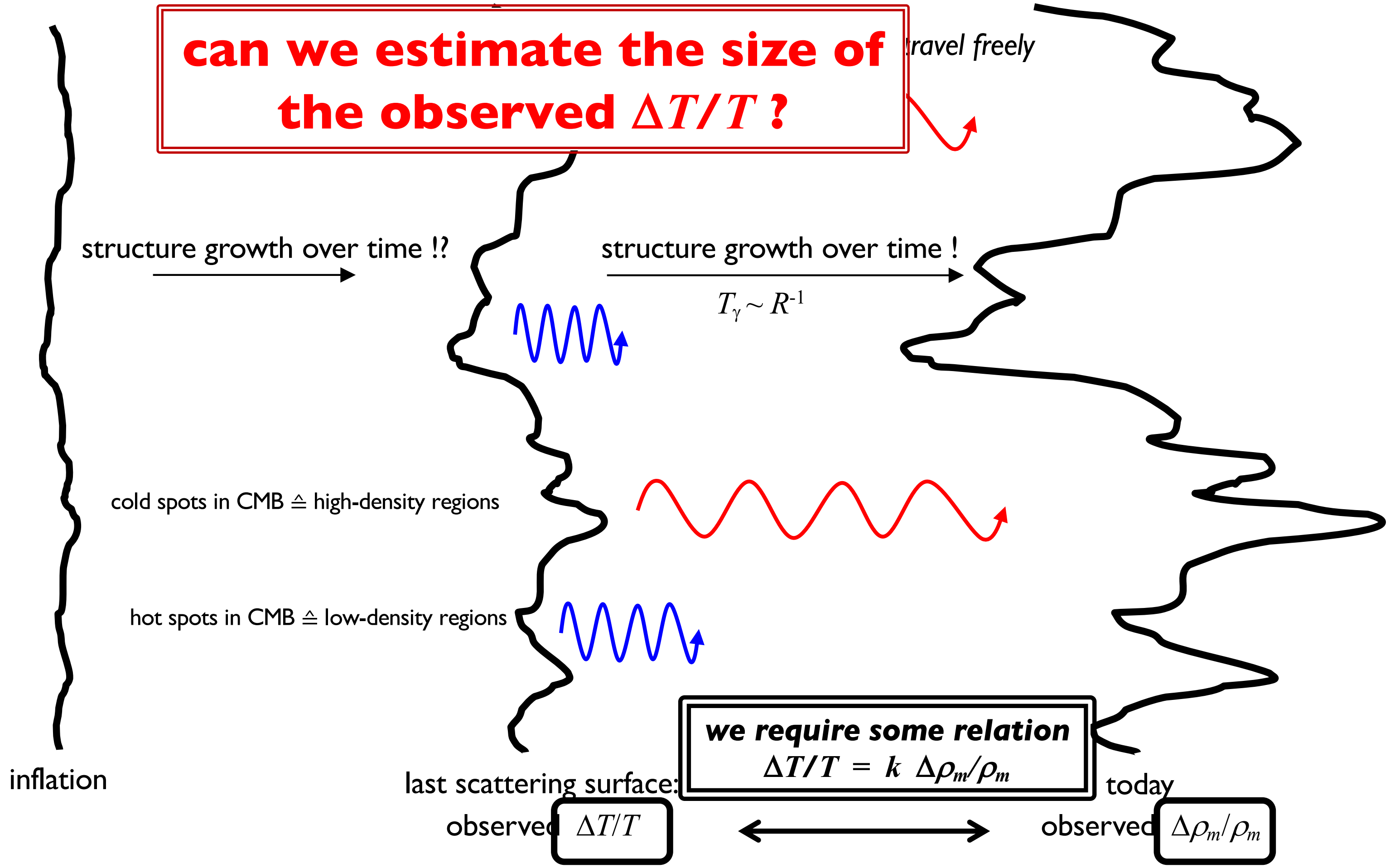


- seed inhomogeneities and their relation to temperature fluctuations:
  - primordial matter perturbations are amplified via gravity
  - intrinsic fluctuations in CMB are conserved

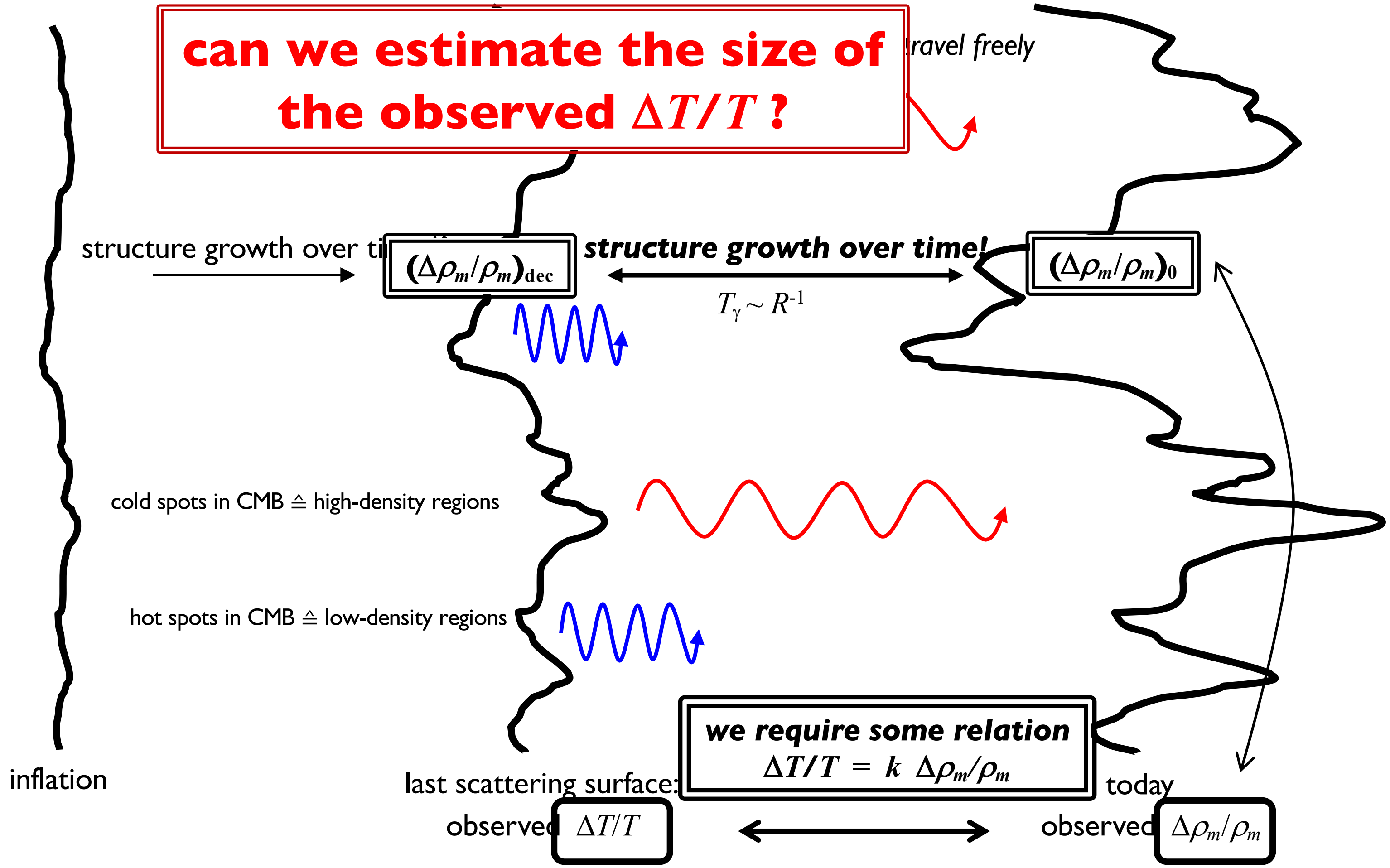
can we estimate the size of the observed $\Delta T/T$?



- seed inhomogeneities and their relation to temperature fluctuations:
  - primordial matter perturbations are amplified via gravity
  - intrinsic fluctuations in CMB are conserved



- seed inhomogeneities and their relation to temperature fluctuations:
  - primordial matter perturbations are amplified via gravity
  - intrinsic fluctuations in CMB are conserved



- (seed) inhomogeneities and their relation to temperature fluctuations:

observed $(\Delta\rho_m/\rho_m)_0$

- (seed) inhomogeneities and their relation to temperature fluctuations:

observed $(\Delta\rho_m/\rho_m)_0$

↓ *theoretical structure formation*

$(\Delta\rho_m/\rho_m)_{\mathrm{dec}}$

- (seed) inhomogeneities and their relation to temperature fluctuations:

observed $(\Delta\rho_m/\rho_m)_0$

↓ *theoretical structure formation*

$(\Delta\rho_m/\rho_m)_{\rm dec}$ → predicted $(\Delta T/T)_{\rm dec}$

some relation

$$\Delta T/T = k\ \Delta\rho_m/\rho_m$$

- (seed) inhomogeneities and their relation to temperature fluctuations:

observed $(\Delta\rho_m/\rho_m)_0$

↓ *theoretical structure formation*

$(\Delta\rho_m/\rho_m)_{\rm dec}$

→ *some relation* $\Delta T/T = k\ \Delta\rho_m/\rho_m$

predicted $(\Delta T/T)_{\rm dec}$

↑ *radiation remains thermal*

predicted $(\Delta T/T)_0 = (\Delta T/T)_{\rm dec}$

- (seed) inhomogeneities and their relation to temperature fluctuations:

observed $(\Delta\rho_m/\rho_m)_0$

predicted $(\Delta T/T)_0 = (\Delta T/T)_{dec}$

a) theoretical structure formation

radiation remains thermal

$(\Delta\rho_m/\rho_m)_{dec}$

predicted $(\Delta T/T)_{dec}$

?

b) some relation

$$\Delta T/T = k \; \Delta\rho_m/\rho_m$$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with} \quad \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution*: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$

*for matter dominated Universe with $\Omega_m \approx 1$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

- solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
- today (lower limit!): $\delta_{m,0} \geq 1$
- decoupling: $z_{dec} \approx 1100$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G \rho_m \delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

- solution: $\delta_{m,0} = \delta_{m,\text{dec}}\, a$
- today (lower limit!): $\delta_{m,0} \geq 1$
- decoupling: $z_{dec} \approx 1100$

$\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\text{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

$\Rightarrow$ $\delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$?

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G \rho_m \delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

$\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

a) relation of $\Delta\rho_m/\rho_m$ to $\Delta\rho_r/\rho_r$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k \;\Delta\rho_m/\rho_m$

  a) relation of $\Delta\rho_m/\rho_m$ to $\Delta\rho_r/\rho_r$

  b) relation of $\Delta\rho_r/\rho_r$ to $\Delta T/T$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G \rho_m \delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

- solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
- today (lower limit!): $\delta_{m,0} \geq 1$
- decoupling: $z_{dec} \approx 1100$

$\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k \; \Delta\rho_m/\rho_m$

a) relation of $\Delta\rho_m/\rho_m$ to $\Delta\rho_r/\rho_r$

$$\rho_m \propto R^{-3}$$

$$\rho_r \propto R^{-4}$$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

• solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$

• today (lower limit!): $\delta_{m,0} \geq 1$

• decoupling: $z_{dec} \approx 1100$

$\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

a) relation of $\Delta\rho_m/\rho_m$ to $\Delta\rho_r/\rho_r$

$$\rho_m \propto R^{-3} \Rightarrow \Delta\rho_m \propto -3R^{-2}\Delta R$$

$$\rho_r \propto R^{-4} \Rightarrow \Delta\rho_r \propto -4R^{-3}\Delta R$$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with} \quad \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

• solution: $\delta_{m,0} = \delta_{m,\text{dec}}\, a$

• today (lower limit!): $\delta_{m,0} \geq 1$

• decoupling: $z_{dec} \approx 1100$

$\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

a) relation of $\Delta\rho_m/\rho_m$ to $\Delta\rho_r/\rho_r$

$$\rho_m \propto R^{-3} \Rightarrow \Delta\rho_m \propto -3R^{-2}\Delta R$$

$$\rho_r \propto R^{-4} \Rightarrow \Delta\rho_r \propto -4R^{-3}\Delta R$$

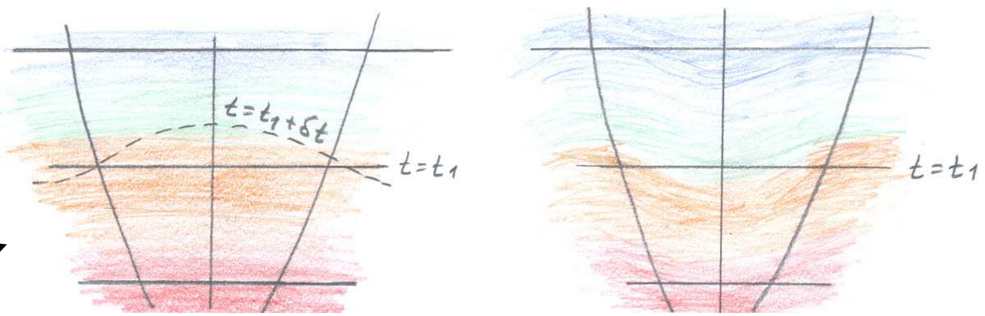


Figure 1: For adiabatic perturbations, the conditions in the perturbed universe (right) at $(t_1, \boldsymbol{x})$ equal conditions in the (homogeneous) background universe (left) at some time $t_1 + \delta t(\boldsymbol{x})$.

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

$\Rightarrow \quad \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k \ \Delta\rho_m/\rho_m$

a) relation of $\Delta\rho_m/\rho_m$ to $\Delta\rho_r/\rho_r$

$$\rho_m \propto R^{-3} \Rightarrow \Delta\rho_m \propto -3R^{-2}\Delta R = -3\rho_m \frac{\Delta R}{R}$$

$$\rho_r \propto R^{-4} \Rightarrow \Delta\rho_r \propto -4R^{-3}\Delta R = -4\rho_r \frac{\Delta R}{R}$$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

  a) relation of $\Delta\rho_m/\rho_m$ to $\Delta\rho_r/\rho_r$

$$\rho_m \propto R^{-3} \Rightarrow \Delta\rho_m \propto -3R^{-2}\Delta R = -3\rho_m\frac{\Delta R}{R} \Rightarrow \frac{\Delta\rho_m}{\rho_m} = -3\frac{\Delta R}{R}$$

$$\rho_r \propto R^{-4} \Rightarrow \Delta\rho_r \propto -4R^{-3}\Delta R = -4\rho_r\frac{\Delta R}{R} \Rightarrow \frac{\Delta\rho_r}{\rho_r} = -4\frac{\Delta R}{R}$$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\text{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

a) relation of $\Delta\rho_m/\rho_m$ to $\Delta\rho_r/\rho_r$

$$\frac{\Delta\rho_m}{\rho_m} = -3\frac{\Delta R}{R}$$

$$\frac{\Delta\rho_r}{\rho_r} = -4\frac{\Delta R}{R}$$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

- solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
- today (lower limit!): $\delta_{m,0} \geq 1$
- decoupling: $z_{dec} \approx 1100$

$\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

a) relation of $\Delta\rho_m/\rho_m$ to $\Delta\rho_r/\rho_r$

$$\left.\begin{aligned}\frac{\Delta\rho_m}{\rho_m} &= -3\frac{\Delta R}{R}\\ \frac{\Delta\rho_r}{\rho_r} &= -4\frac{\Delta R}{R}\end{aligned}\right\} \quad \frac{\Delta\rho_m}{\rho_m} = \frac{3}{4}\frac{\Delta\rho_r}{\rho_r}$$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

  a) adiabatic perturbations: $\Delta\rho_m/\rho_m = (3/4)\ \Delta\rho_r/\rho_r$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \qquad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

  a) *adiabatic?* perturbations: $\Delta\rho_m/\rho_m = (3/4)\ \Delta\rho_r/\rho_r$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

  a) adiabatic perturbations: $\Delta\rho_m/\rho_m = (3/4)\ \Delta\rho_r/\rho_r$

  b) relation of $\Delta\rho_r/\rho_r$ to $\Delta T/T$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

  a) adiabatic perturbations: $\Delta\rho_m/\rho_m = (3/4)\ \Delta\rho_r/\rho_r$

  b) relation of $\Delta\rho_r/\rho_r$ to $\Delta T/T$

  radiation density: $\rho_r \propto T^4$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G \rho_m \delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

  a) adiabatic perturbations: $\Delta\rho_m/\rho_m = (3/4)\ \Delta\rho_r/\rho_r$

  b) relation of $\Delta\rho_r/\rho_r$ to $\Delta T/T$

  radiation density: $\rho_r \propto T^4 \Rightarrow \Delta\rho_r \propto 4T^3\Delta T = 4\dfrac{\rho_r}{T}\Delta T \Rightarrow \dfrac{\Delta\rho_r}{\rho_r} = 4\dfrac{\Delta T}{T}$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow$ $\delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k \; \Delta\rho_m/\rho_m$

  a) adiabatic perturbations: $\Delta\rho_m/\rho_m = (3/4)\, \Delta\rho_r/\rho_r$

  b) relation $\Delta\rho_r/\rho_r = 4\, \Delta T/T$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with } \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k \;\; \Delta\rho_m/\rho_m$

  a) adiabatic perturbations: $\Delta\rho_m/\rho_m = (3/4)\,\Delta\rho_r/\rho_r$

  b) relation $\Delta\rho_r/\rho_r = 4\,\Delta T/T$

  $$\frac{\Delta T}{T} = \frac{1}{3}\frac{\Delta\rho_m}{\rho_m}$$

- theoretical structure formation (see "LSS" lecture)

$$\boxed{\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G\rho_m\delta_m} \quad \text{with} \quad \delta_m = \frac{\Delta\rho_m}{\rho_m}$$

  - solution: $\delta_{m,0} = \delta_{m,\mathrm{dec}}\, a$
  - today (lower limit!): $\delta_{m,0} \geq 1$
  - decoupling: $z_{dec} \approx 1100$

  $\Rightarrow \delta_{m,dec} \geq 10^{-3}$ (lower limit!)

- relation $\Delta T/T = k\ \Delta\rho_m/\rho_m$

  a) adiabatic perturbations: $\Delta\rho_m/\rho_m = (3/4)\ \Delta\rho_r/\rho_r$

  b) relation $\Delta\rho_r/\rho_r = 4\ \Delta T/T$

  $$\Rightarrow \frac{\Delta T}{T} = \frac{1}{3}\frac{\Delta\rho_m}{\rho_m}$$

putting all together again...

- theoretical structure formation (see "LSS" lecture)

observed $(\Delta\rho_m/\rho_m)_0 \geq 1$

theoretical structure formation

$\delta_{m,0} = \delta_{m,\mathrm{dec}} / (1+z_{dec})$

$(\Delta\rho_m/\rho_m)_{\mathrm{dec}} \geq 10^{-3}$ → predicted $(\Delta T/T)_{\mathrm{dec}} \geq 10^{-3}$

adiabatic pertubations

$\Delta T/T = (1/3)\ \Delta\rho_m/\rho_m$

radiation remains thermal

predicted $(\Delta T/T)_0 \geq 10^{-3}$

- theoretical structure formation (see "LSS" lecture)

observed $(\Delta\rho_m/\rho_m)_0 \geq 1$

predicted $(\Delta T/T)_0 \geq 10^{-3}$

should have been detected in 1970's and 1980's!

theoretical structure formation

$\delta_{m,0} = \delta_{m,\mathrm{dec}} / (1+z_{dec})$

radiation remains thermal

$(\Delta\rho_m/\rho_m)_{\mathrm{dec}} \geq 10^{-3}$ → predicted $(\Delta T/T)_{\mathrm{dec}} \geq 10^{-3}$

adiabatic pertubations

$\Delta T/T = (1/3)\ \Delta\rho_m/\rho_m$

- theoretical structure formation (see "LSS" lecture)

observed $(\Delta T/T)_0 \leq 10^{-5}$

observed $(\Delta\rho_m/\rho_m)_0 \geq 1$

predicted $(\Delta T/T)_0 \geq 10^{-3}$

theoretical structure formation
$\delta_{m,0} = \delta_{m,\mathrm{dec}} / (1+z_{dec})$

radiation remains thermal

$(\Delta\rho_m/\rho_m)_{\mathrm{dec}} \geq 10^{-3}$ → predicted $(\Delta T/T)_{\mathrm{dec}} \geq 10^{-3}$

adiabatic pertubations

$\Delta T/T = (1/3)\ \Delta\rho_m/\rho_m$

- theoretical structure formation (see "LSS" lecture)

observed $(\Delta T/T)_0 \leq 10^{-5}$

predicted $(\Delta T/T)_0 \geq 10^{-3}$

observed $(\Delta\rho_m/\rho_m)_0 \geq 1$

theoretical structure formation

$\delta_{m,0} = \delta_{m,\mathrm{dec}} / (1+z_{dec})$

what's wrong here?

radiation remains thermal

$(\Delta\rho_m/\rho_m)_{\mathrm{dec}} \geq 10^{-3}$ → predicted $(\Delta T/T)_{\mathrm{dec}} \geq 10^{-3}$

adiabatic pertubations

$\Delta T/T = (1/3)\ \Delta\rho_m/\rho_m$

- theoretical structure formation (see "LSS" lecture)

observed $(\Delta T/T)_0 \leq 10^{-5}$

observed $(\Delta\rho_m/\rho_m)_0 \geq 1$

predicted $(\Delta T/T)_0 \geq 10^{-3}$

theoretical structure formation

$\delta_{m,0} = \delta_{m,\mathrm{dec}} / (1+z_{dec})$

what's wrong here?

radiation remains thermal

$(\Delta\rho_m/\rho_m)_{\mathrm{dec}} \geq 10^{-3}$ → predicted $(\Delta T/T)_{\mathrm{dec}} \geq 10^{-3}$

adiabatic pertubations

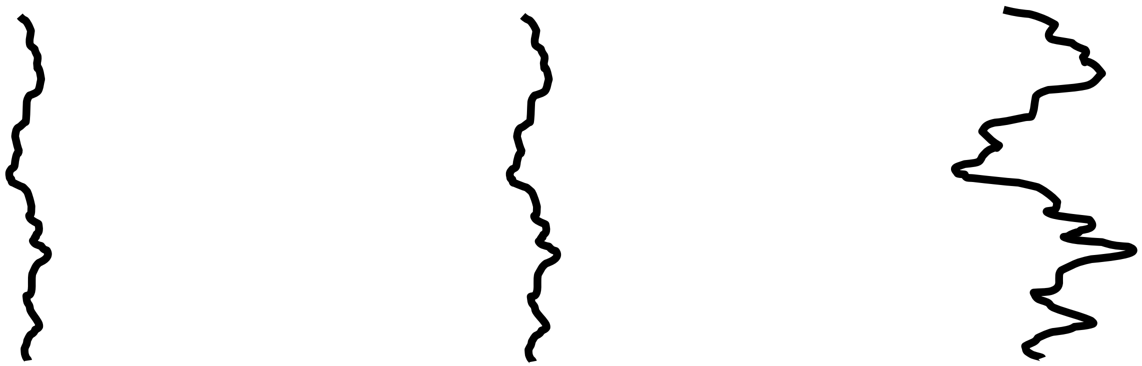
$\Delta T/T = (1/3)\ \Delta\rho_m/\rho_m$

we require some matter that already formed structures before z_{dec}!

- dark matter to the rescue…

inflation | decoupling | today

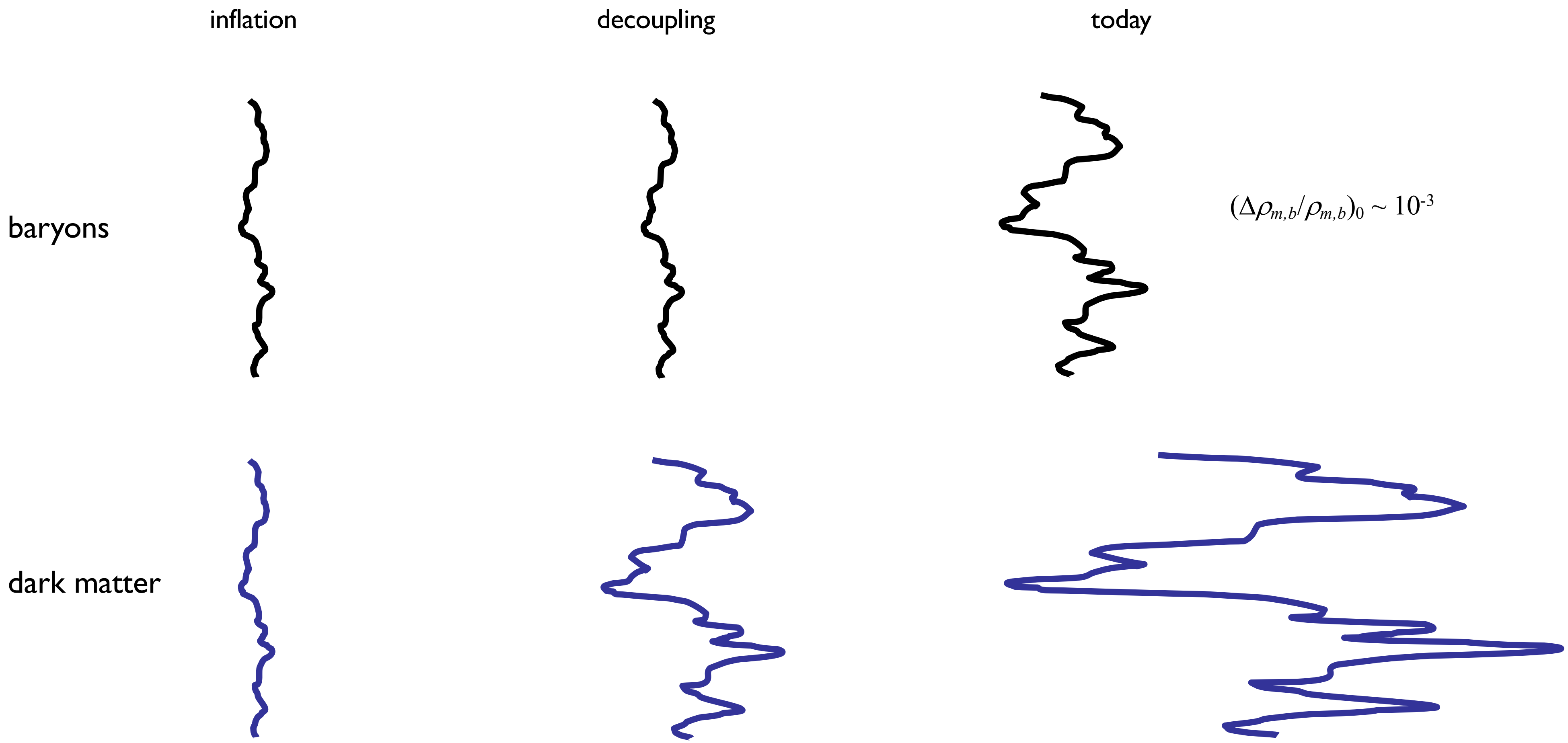
baryons



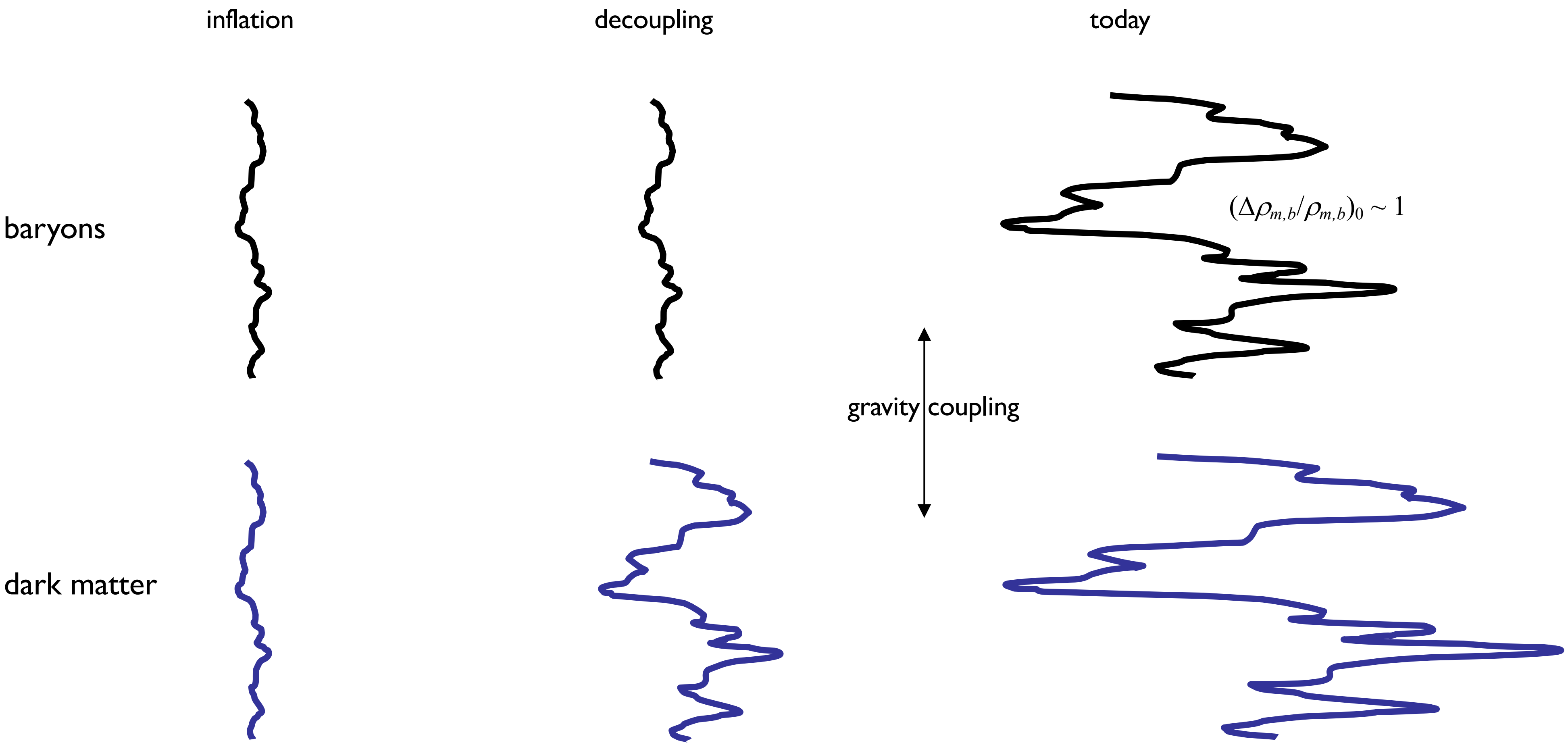
$(\Delta\rho_{m,b}/\rho_{m,b})_0 \sim 10^{-3}$

without dark matter

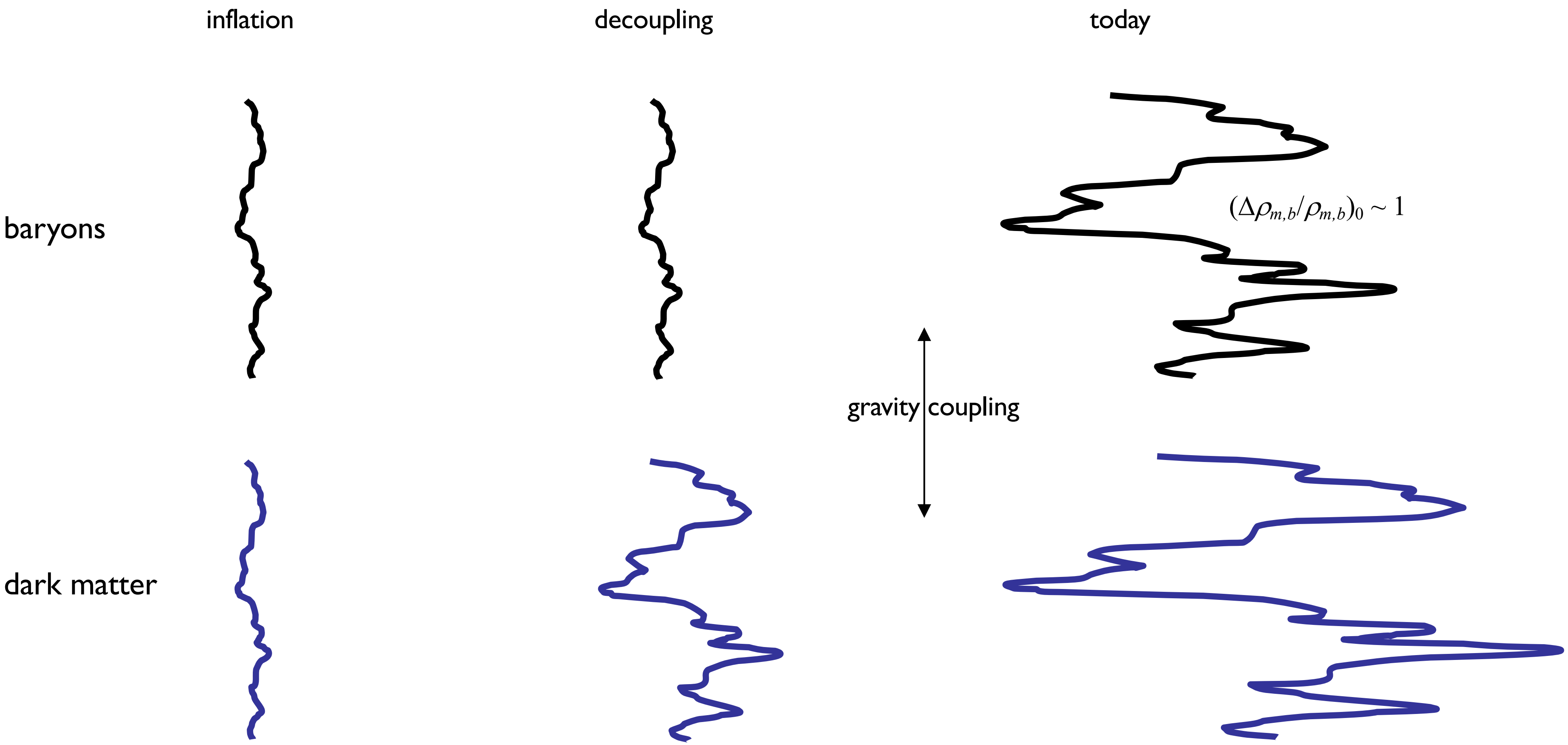
- dark matter to the rescue…



- dark matter to the rescue…

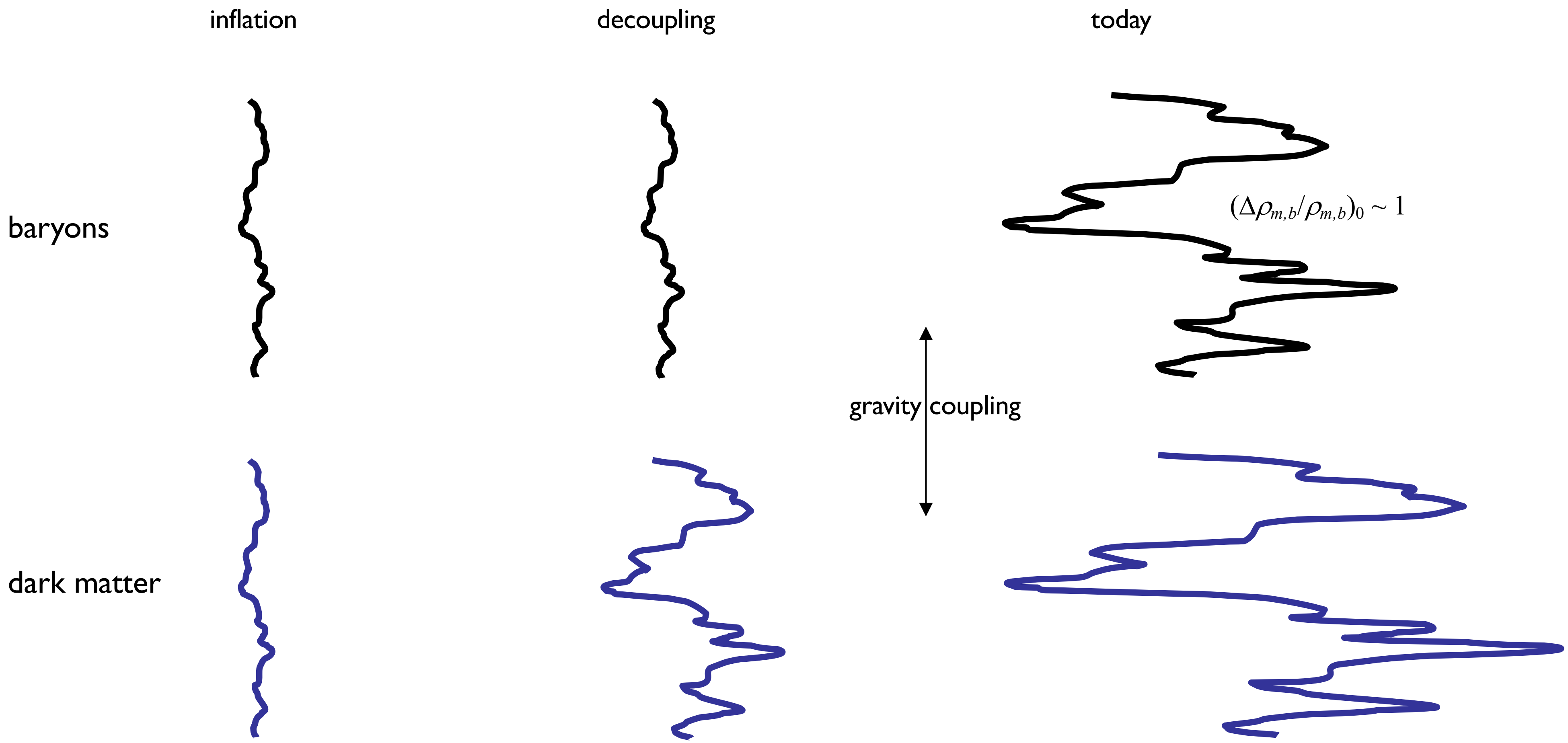


- dark matter to the rescue…



dark matter could form structures prior to (re-)combination

- dark matter to the rescue…



dark matter could form structures prior to (re-)combination

observed $\Delta T/T \approx 10^{-5}$ compatible with $(\Delta\rho_m/\rho_m)_0 > 1$

- discovery
- origin
- **CMB fluctuations**
  - primary (created during inflation):
    - intrinsic fluctuations
    - **how to quantify them?**
    - what's their nature?
    - sensitivity to cosmological parameters?
  - secondary (created after photon decoupling):
    - what's their nature?
    - what's their importance?

- quantifying fluctuations on a sphere?

- quantifying fluctuations on a sphere

$$\frac{\Delta T}{T}(\vartheta,\varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\vartheta,\varphi)$$

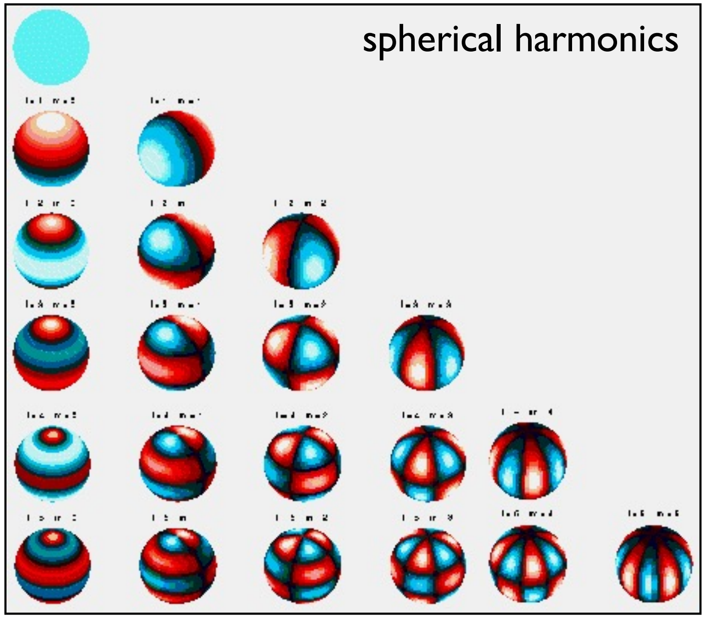
$Y_{lm}(\vartheta,\varphi)$: spherical harmonics

(complete orthonormal set of functions on the surface of a sphere)

$l=0$ → monopole (not measurable)

$l=1$ → dipole (Local Group motion)

$l>1$ → anisotropies we're after!



- quantifying fluctuations on a sphere

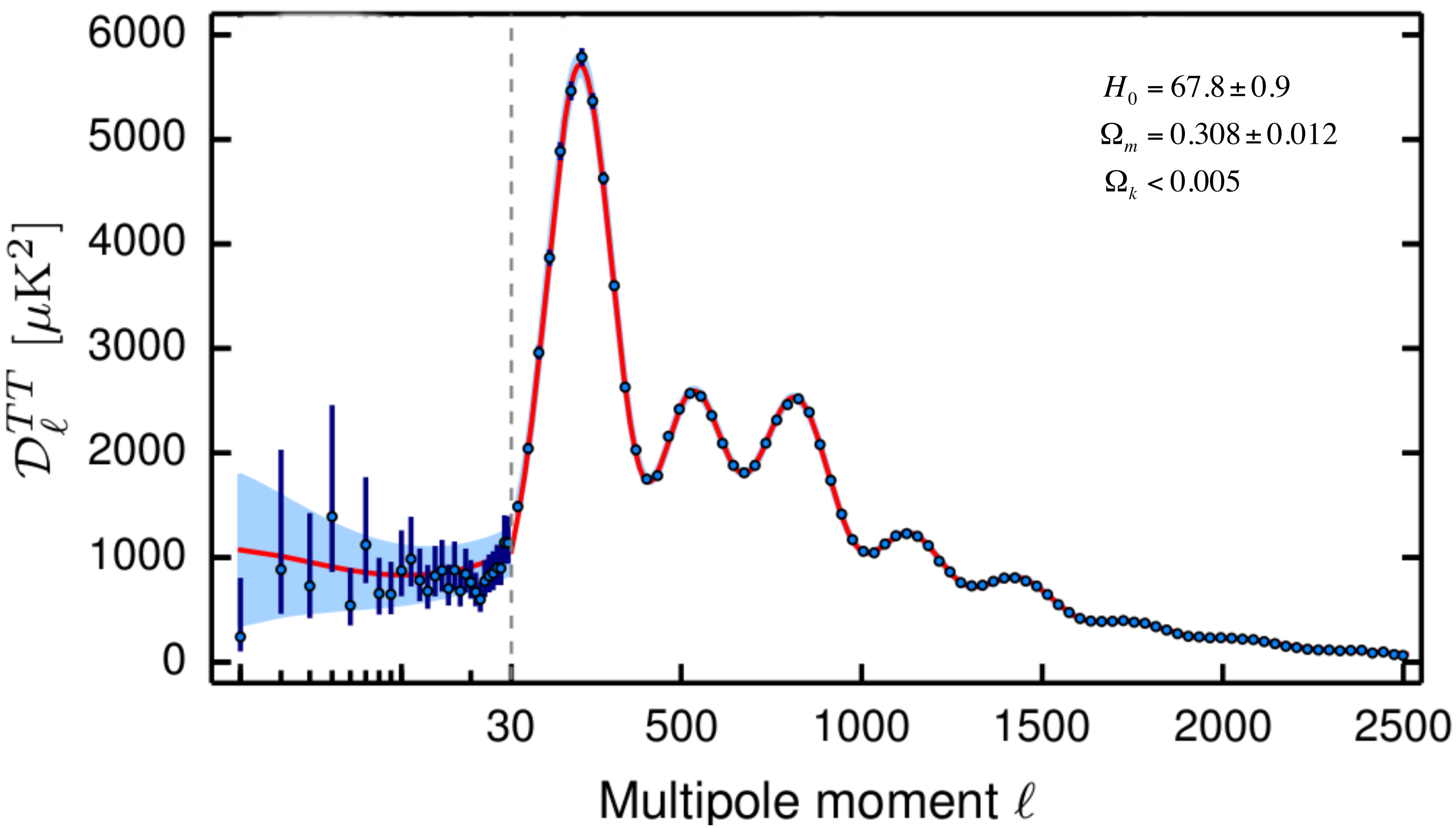
$$\frac{\Delta T}{T}(\vartheta,\varphi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{+l} a_{lm} Y_{lm}(\vartheta,\varphi)$$

isotropy ≙ rotational invariance

$$\boxed{C_l = \frac{1}{2l+1}\sum_{m=-l}^{+l}\left|a_{lm}\right|^2}$$

C_l: power spectrum of temperature fluctuations

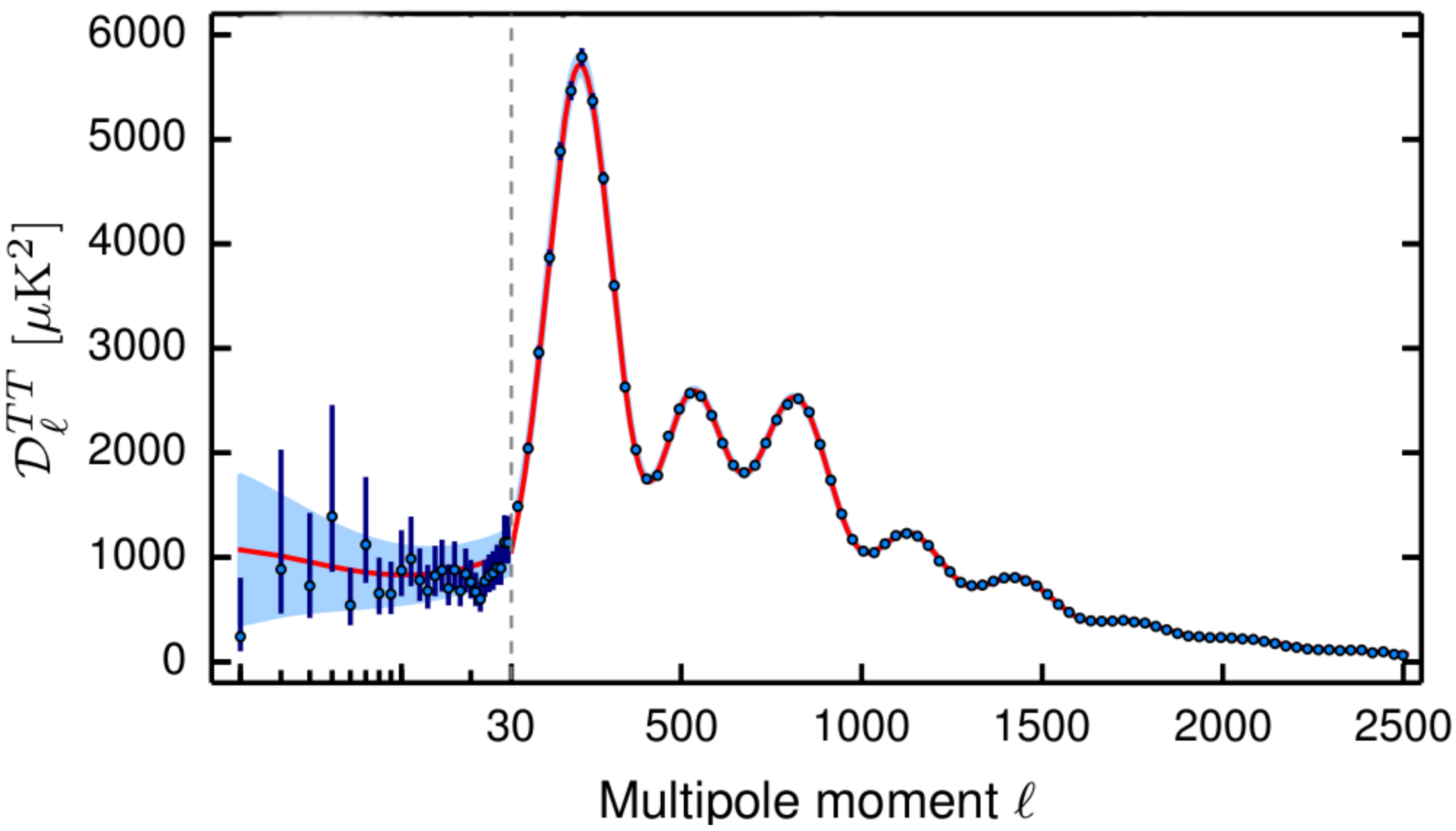
- quantifying fluctuations – Planck 2015 (Ade et al., astro-ph/1502.02114)



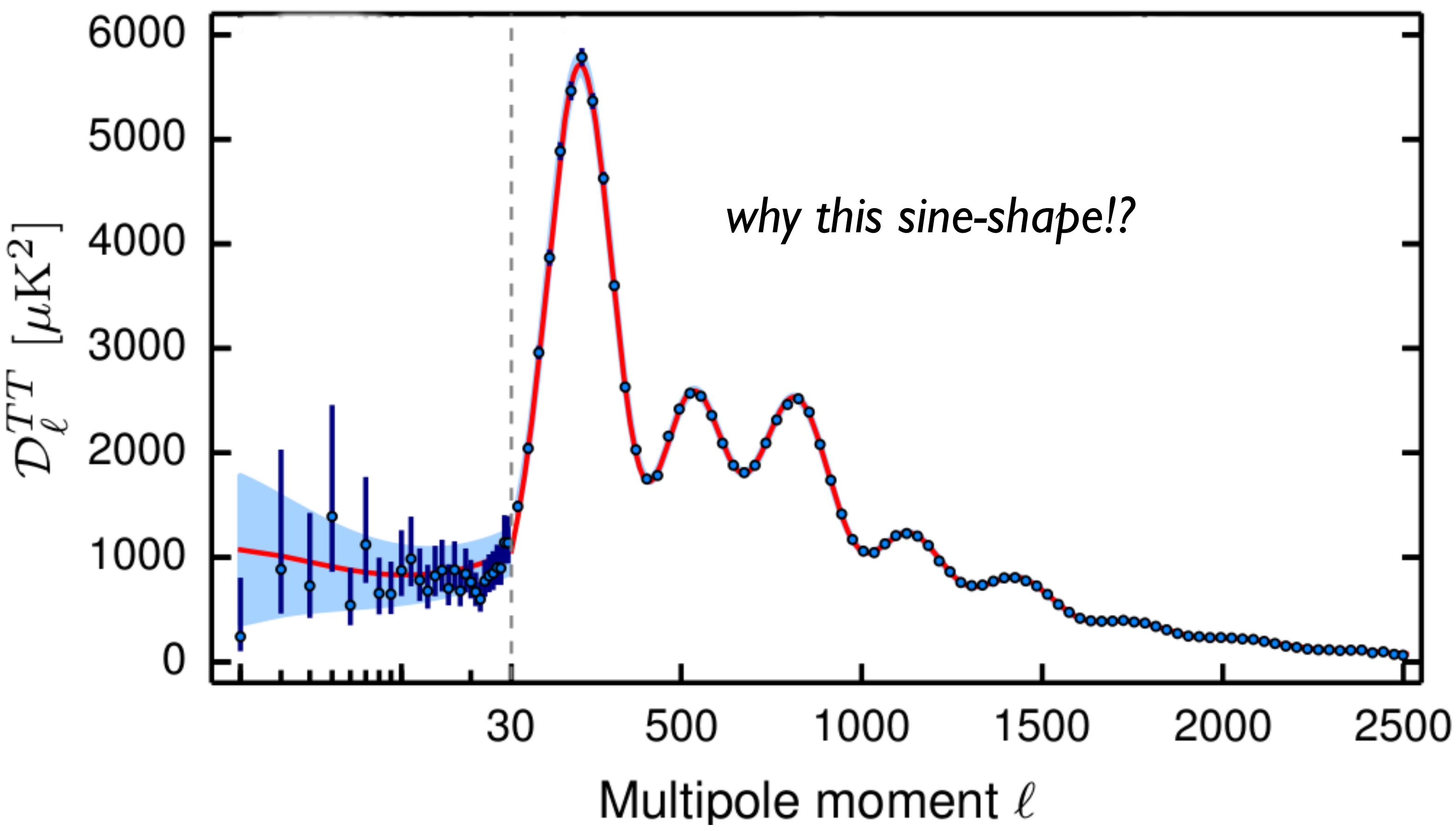
$D_l = \frac{1}{2\pi} l(l+1) C_l$

- discovery
- origin
- **CMB fluctuations**
  - primary (created during inflation):
    - intrinsic fluctuations
    - how to quantify them?
    - **what's their nature?**
    - sensitivity to cosmological parameters?
  - secondary (created after photon decoupling):
    - what's their nature?
    - what's their importance?

- nature of fluctuations



- nature of fluctuations



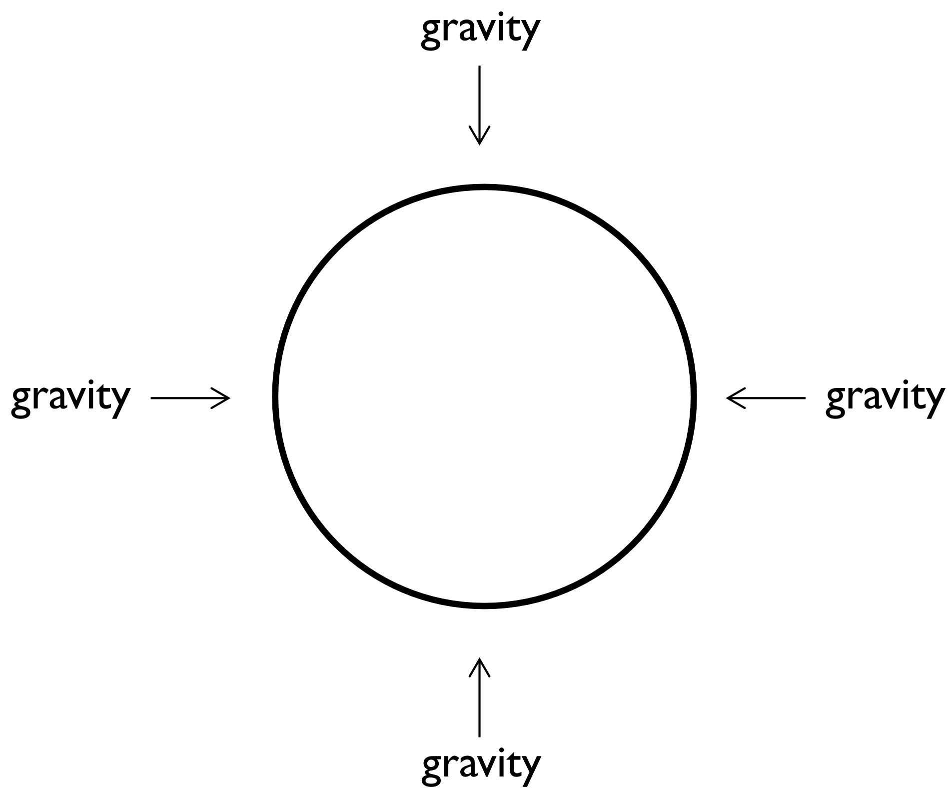
- nature of fluctuations
  - baryonic matter was coupled to radiation prior to $z_{\rm rec} \sim 1330$

- nature of fluctuations
  - baryonic matter was coupled to radiation prior to z_{rec} ~ 1330

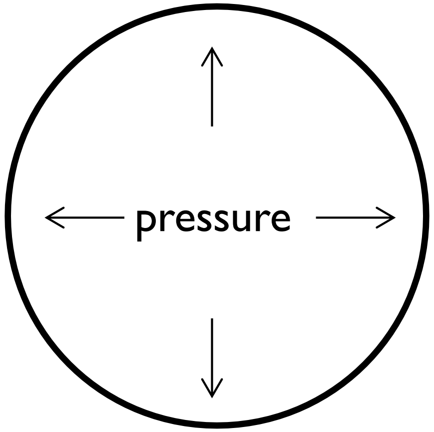
↓ existence of perturbations

baryonic acoustic oscillations

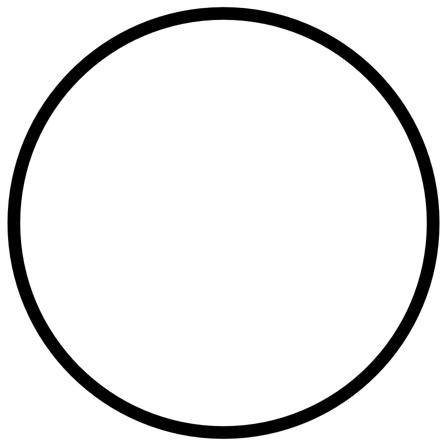
- baryonic acoustic oscillations
  - gravity vs. radiation pressure



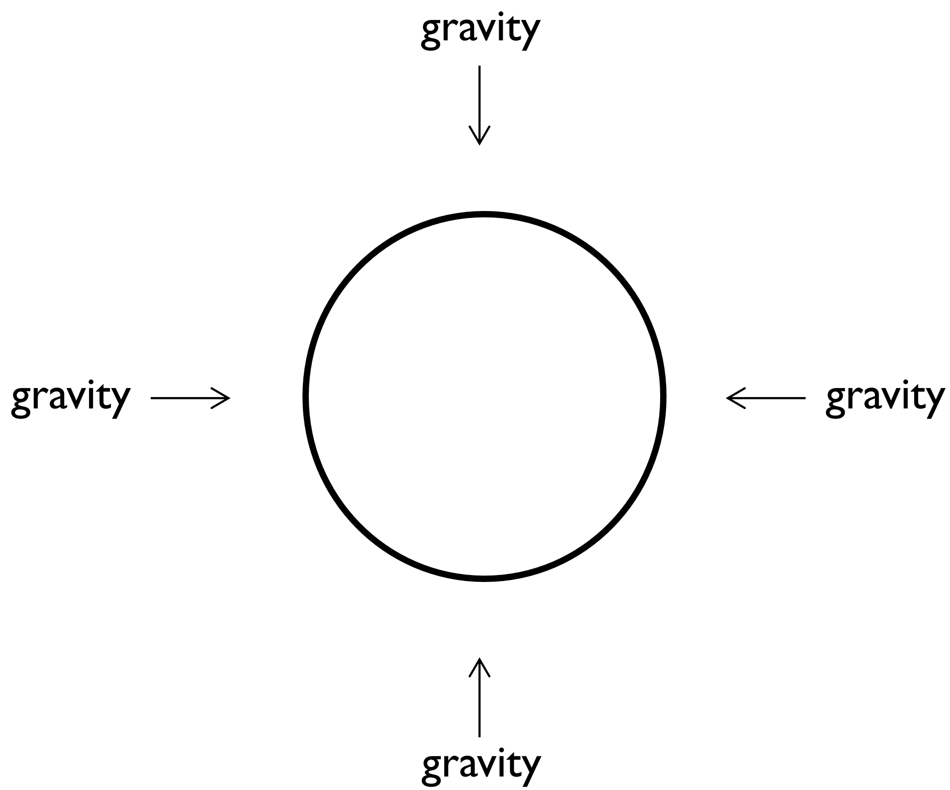
- baryonic acoustic oscillations
  - gravity vs. radiation pressure



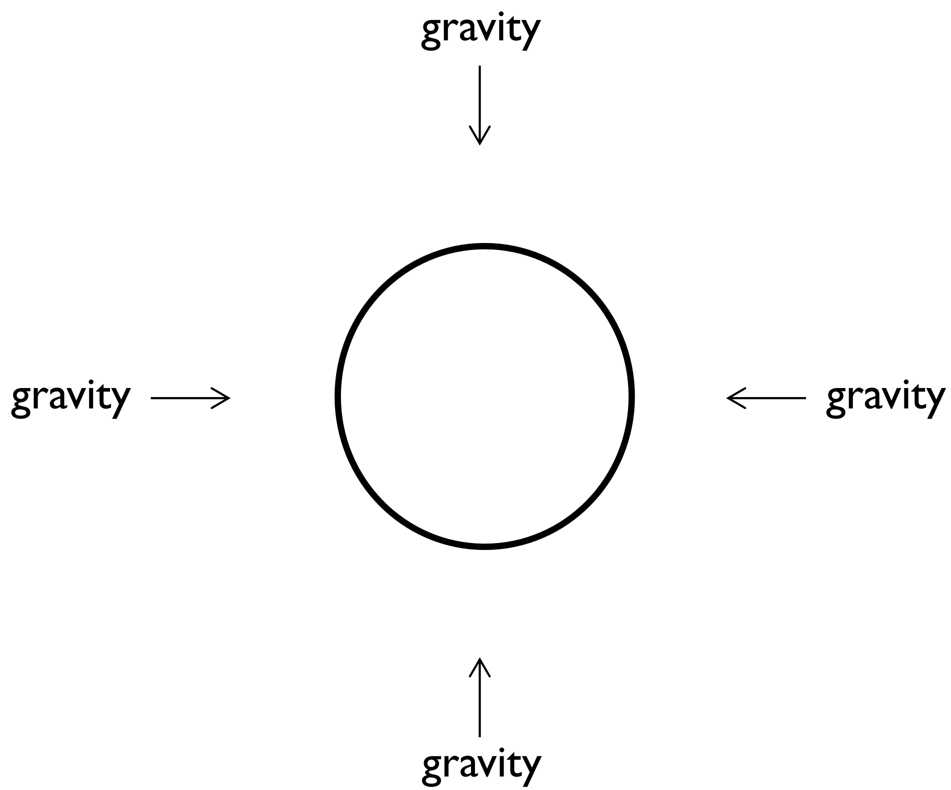
- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations



- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations

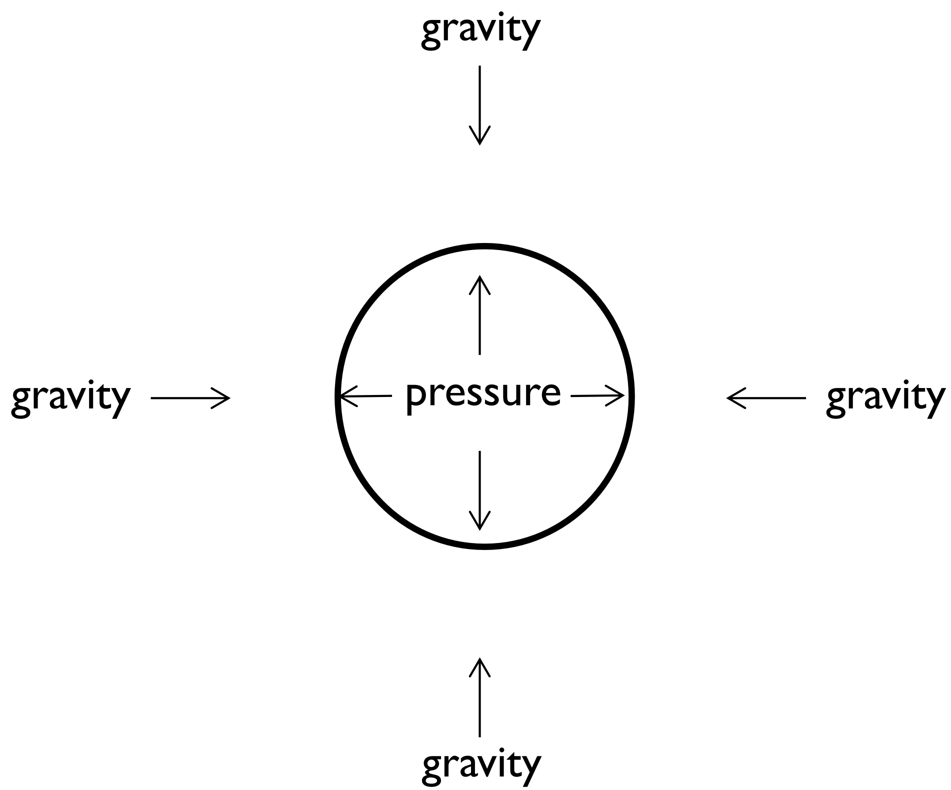


- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations



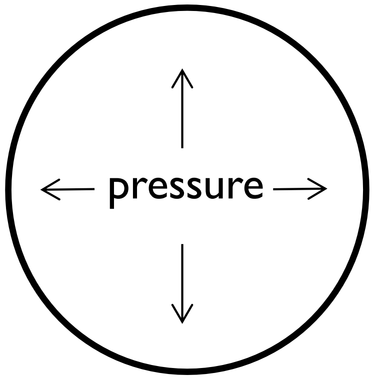
max. compression

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations

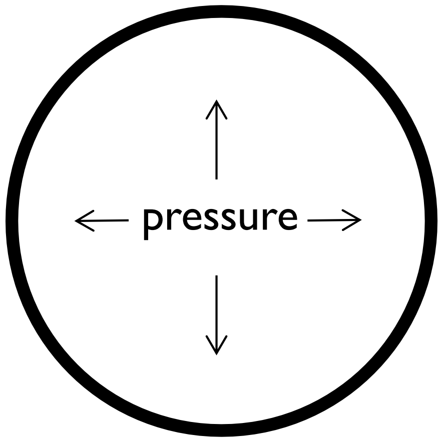


max. compression

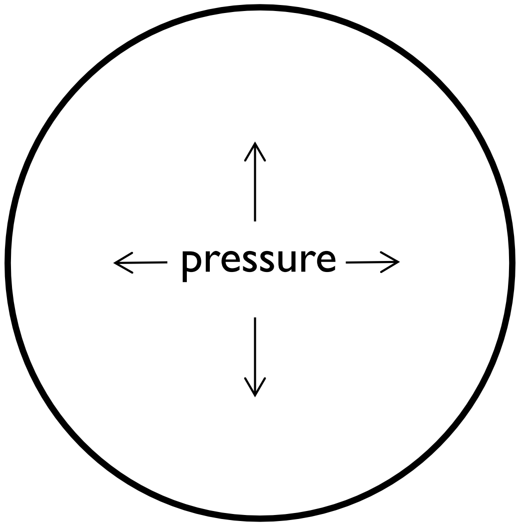
- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations



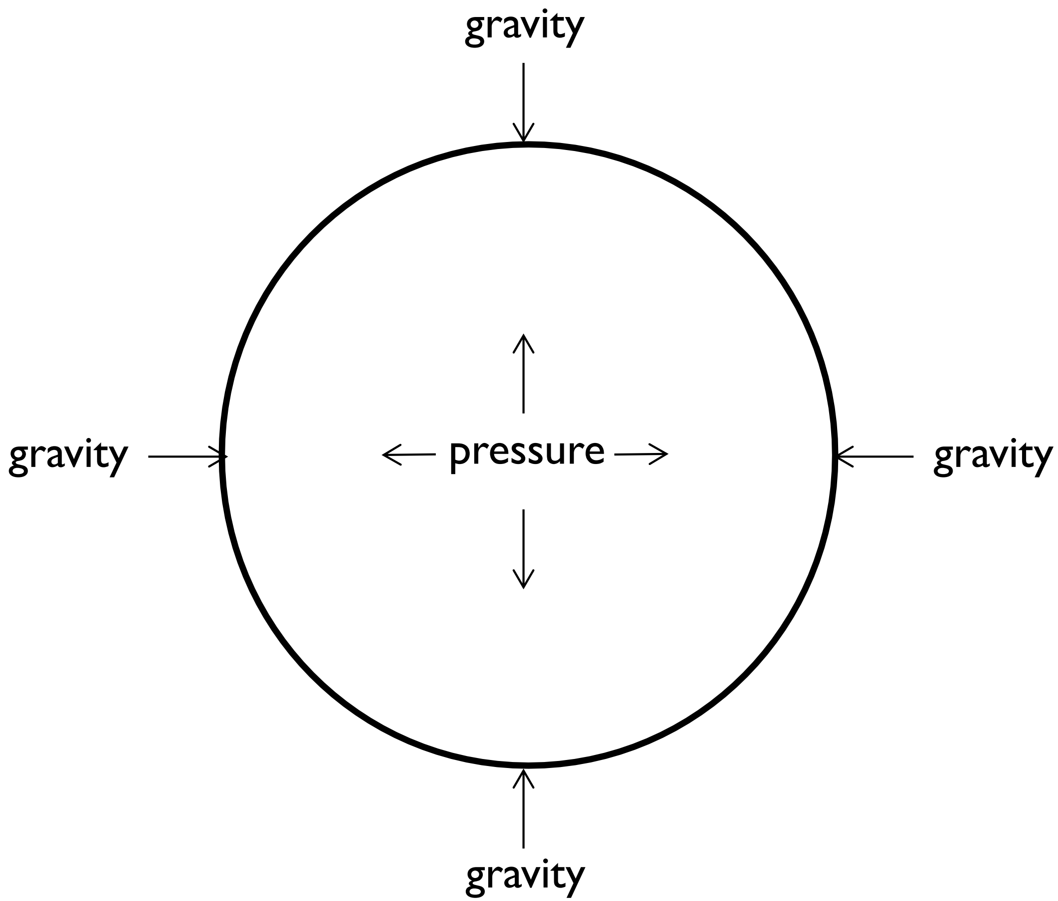
- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations



- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations

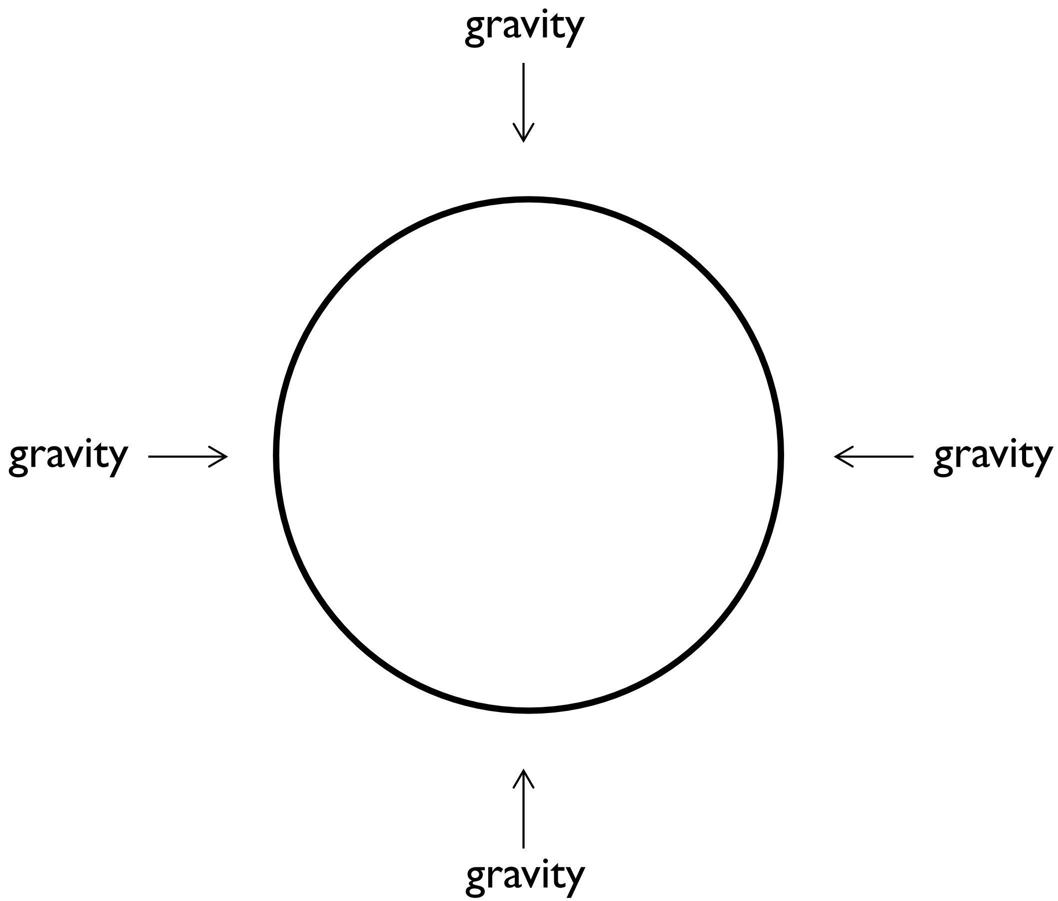


- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations

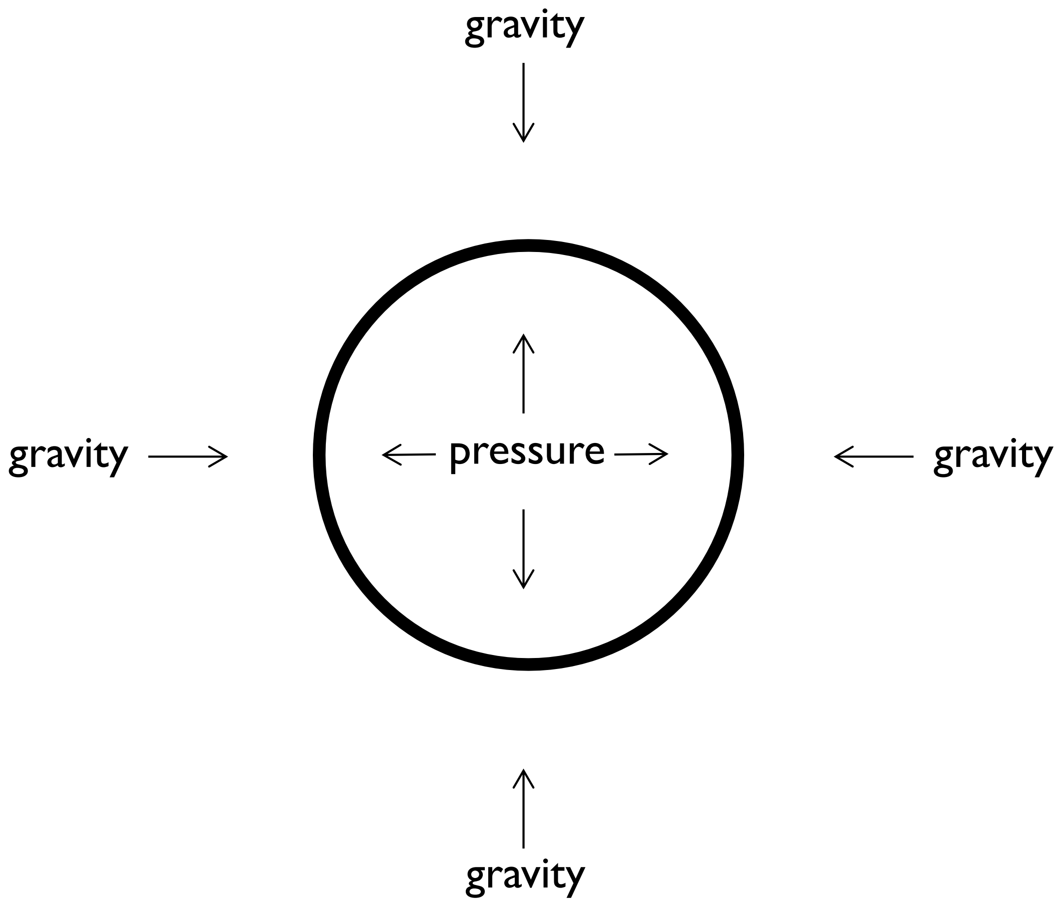


rarefaction

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations



- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations

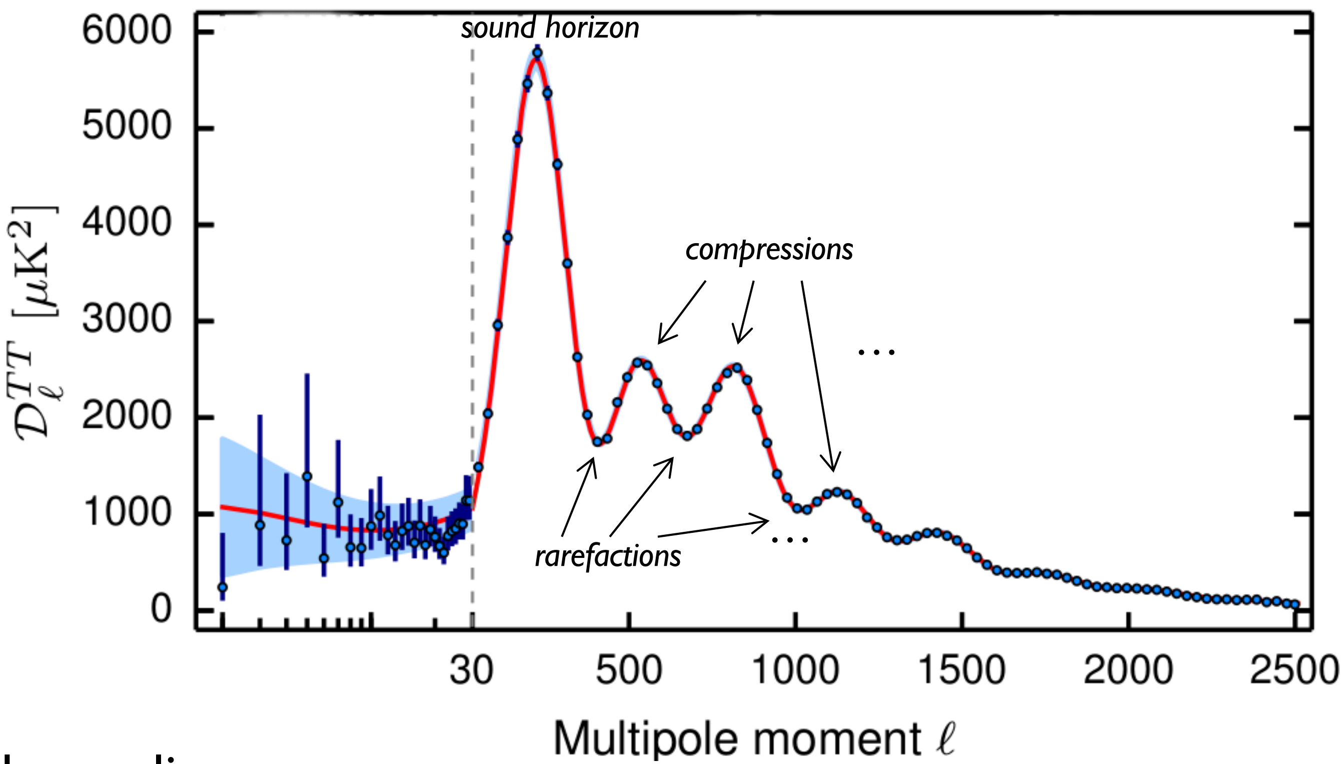


- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations

<u>decoupling:</u>

- oscillations are frozen
- photons are caught at extremes → translation into temperature fluctuations

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations



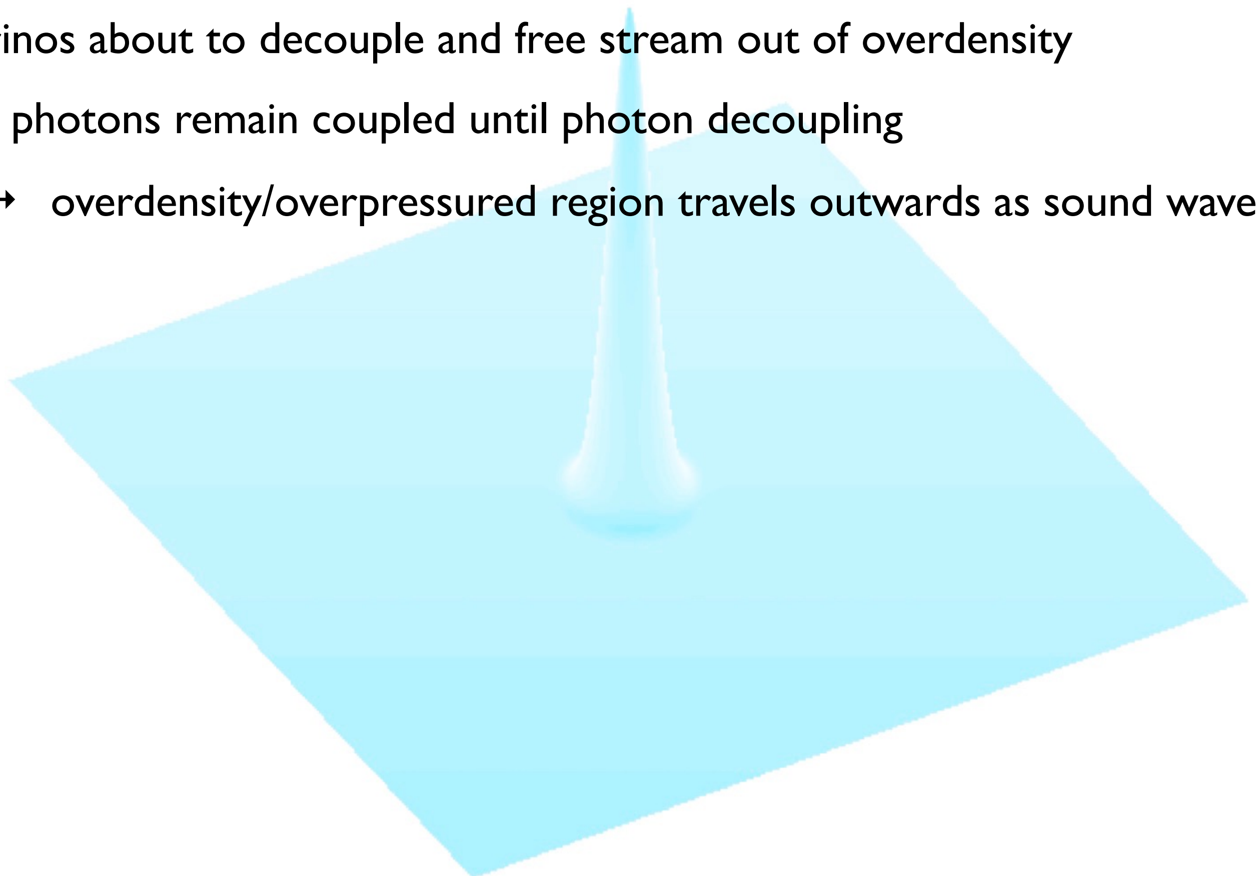
<u>decoupling:</u>

- oscillations are frozen
- photons are caught at extremes → translation into temperature fluctuations

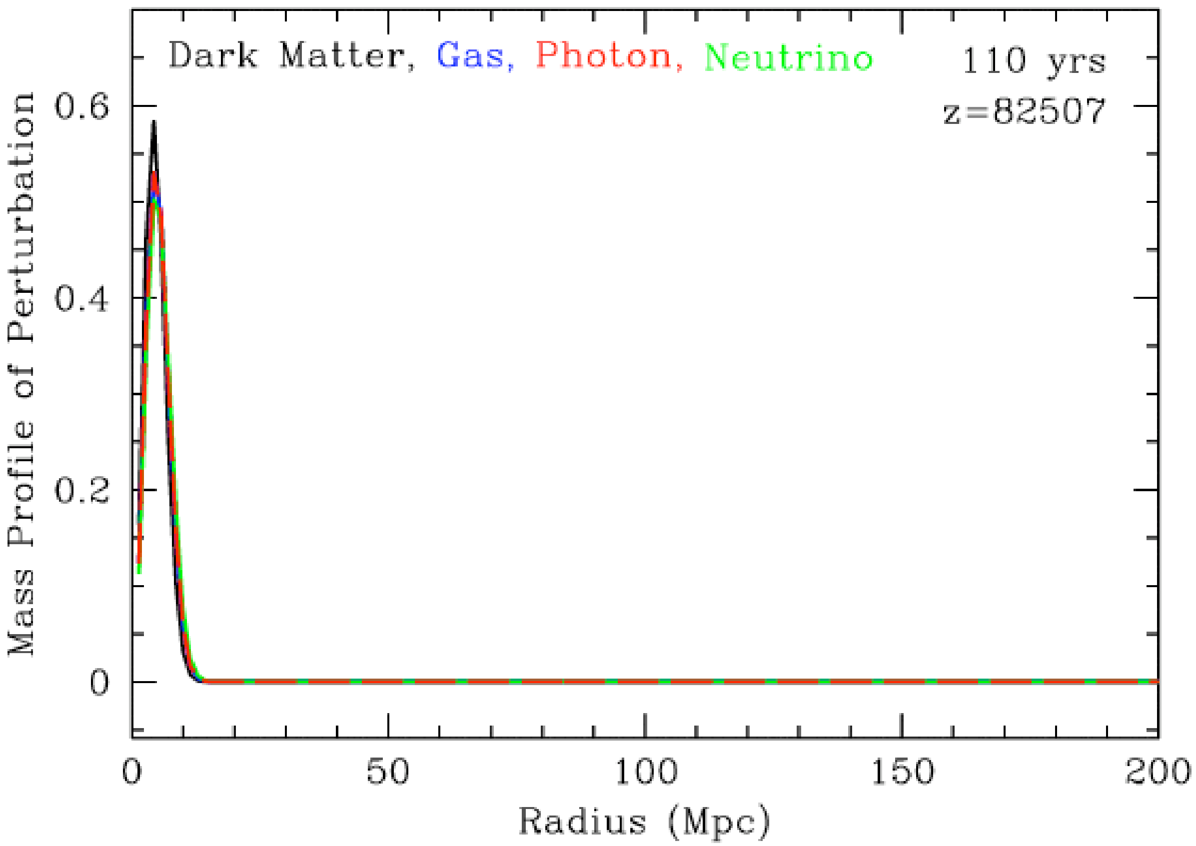
- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves $c_s = \sqrt{\frac{\partial p}{\partial \rho}} \approx \frac{c}{\sqrt{3}}$
  - overdensity in DM, neutrinos, gas & photons

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves $c_s = \sqrt{\frac{\partial p}{\partial \rho}} \approx \frac{c}{\sqrt{3}}$
  - overdensity in DM, neutrinos, gas & photons:
    - DM is decoupled and hence able to gravitationally collapse right away
    - neutrinos about to decouple and free stream out of overdensity
    - gas & photons remain coupled until photon decoupling

      → overdensity/overpressured region travels outwards as sound wave

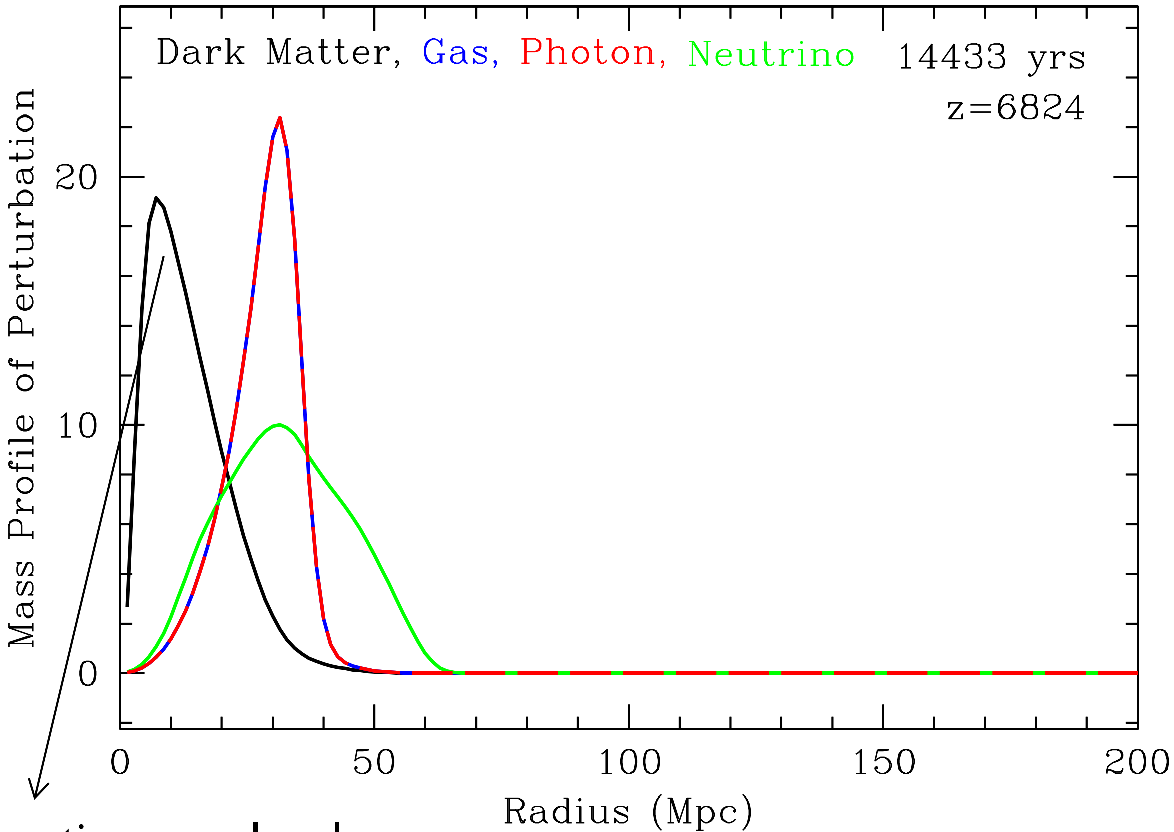


- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves $c_s = \sqrt{\frac{\partial p}{\partial \rho}} \approx \frac{c}{\sqrt{3}}$



Eisenstein et al. (2007)

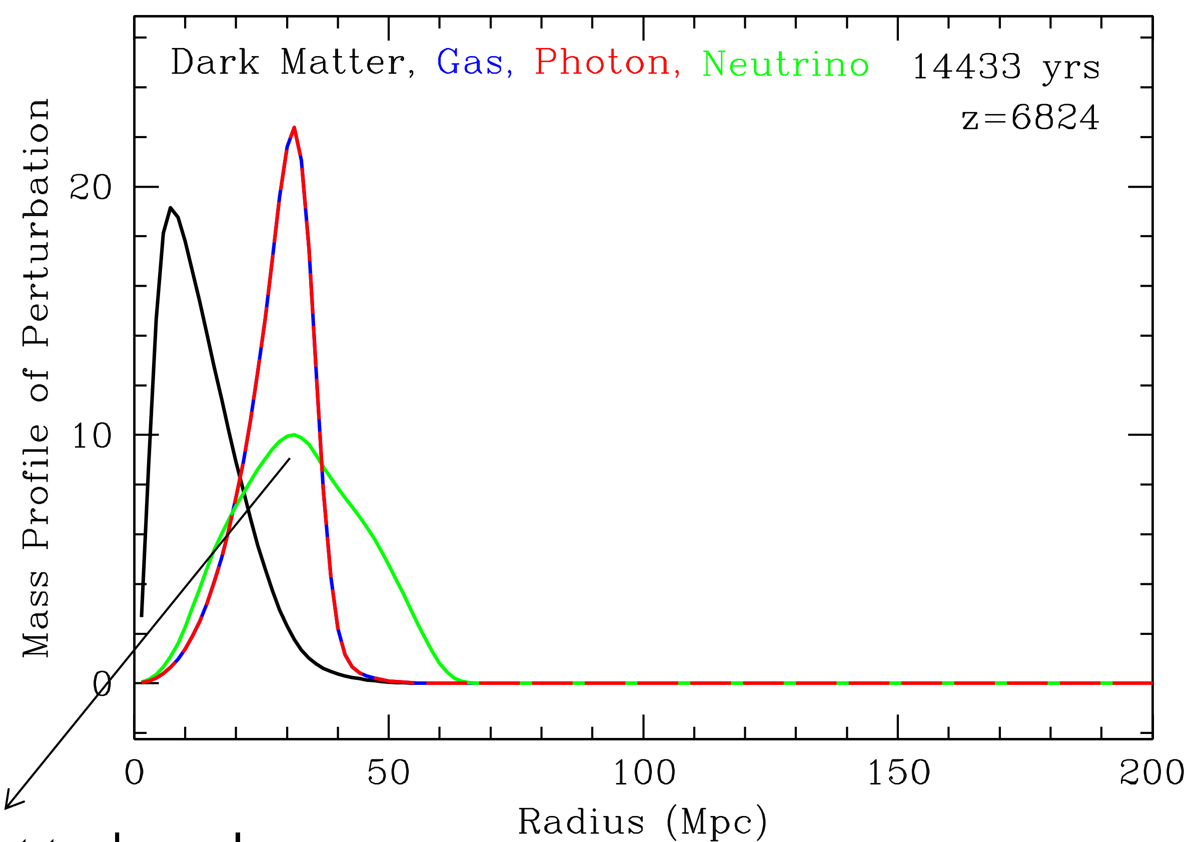
- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



DM decoupled a long time ago already…

Eisenstein et al. (2007)

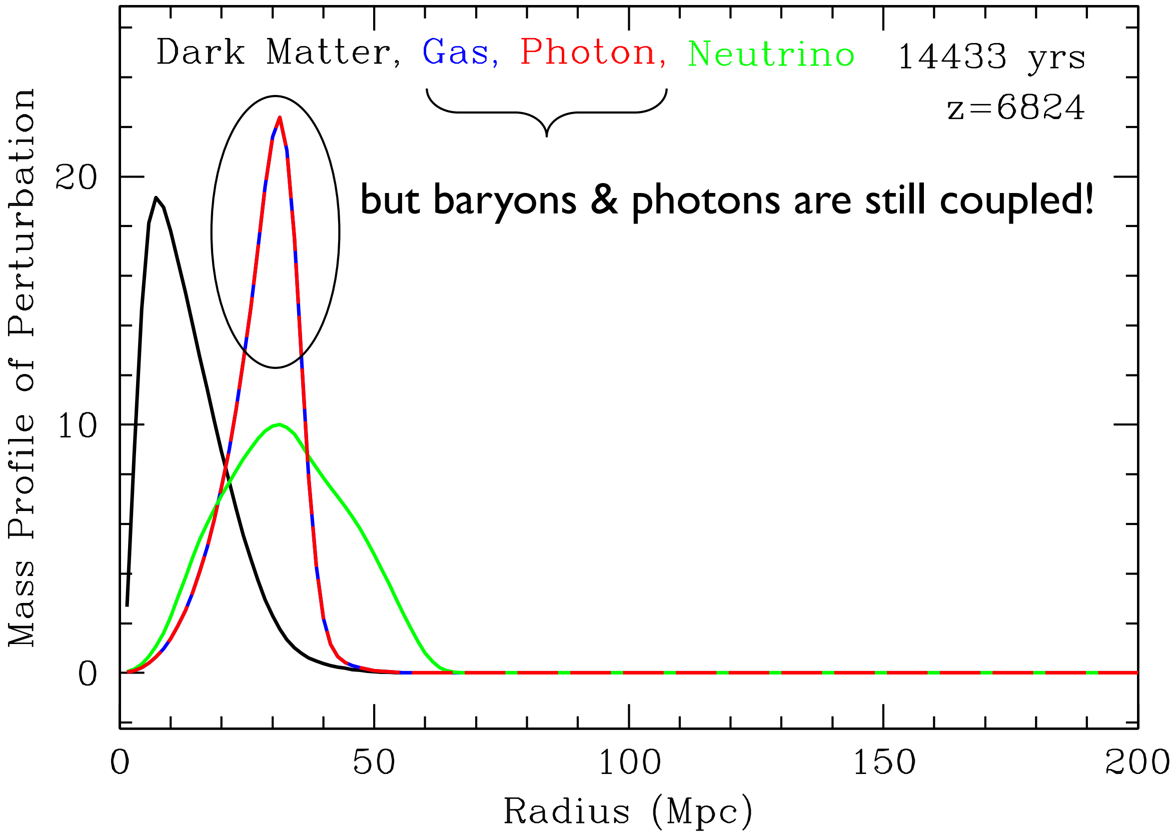
- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



neutrinos are about to decouple…

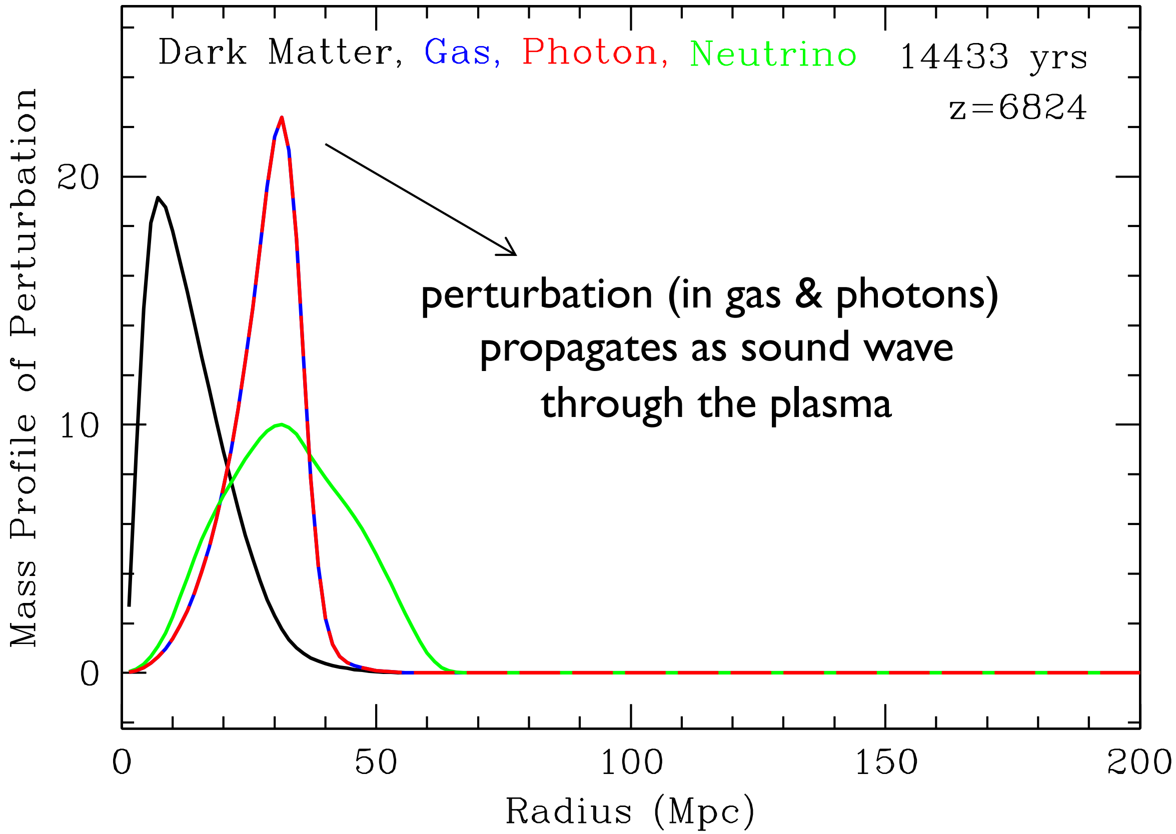
Eisenstein et al. (2007)

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



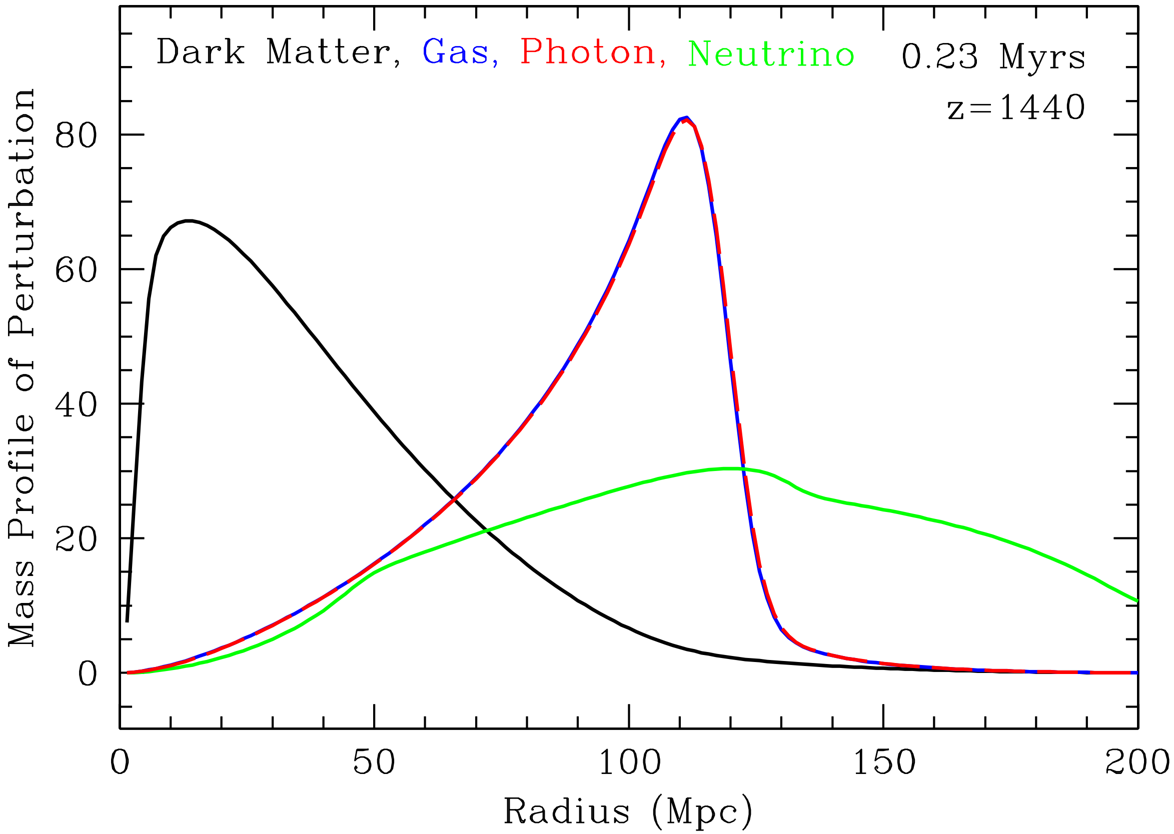
Eisenstein et al. (2007)

- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



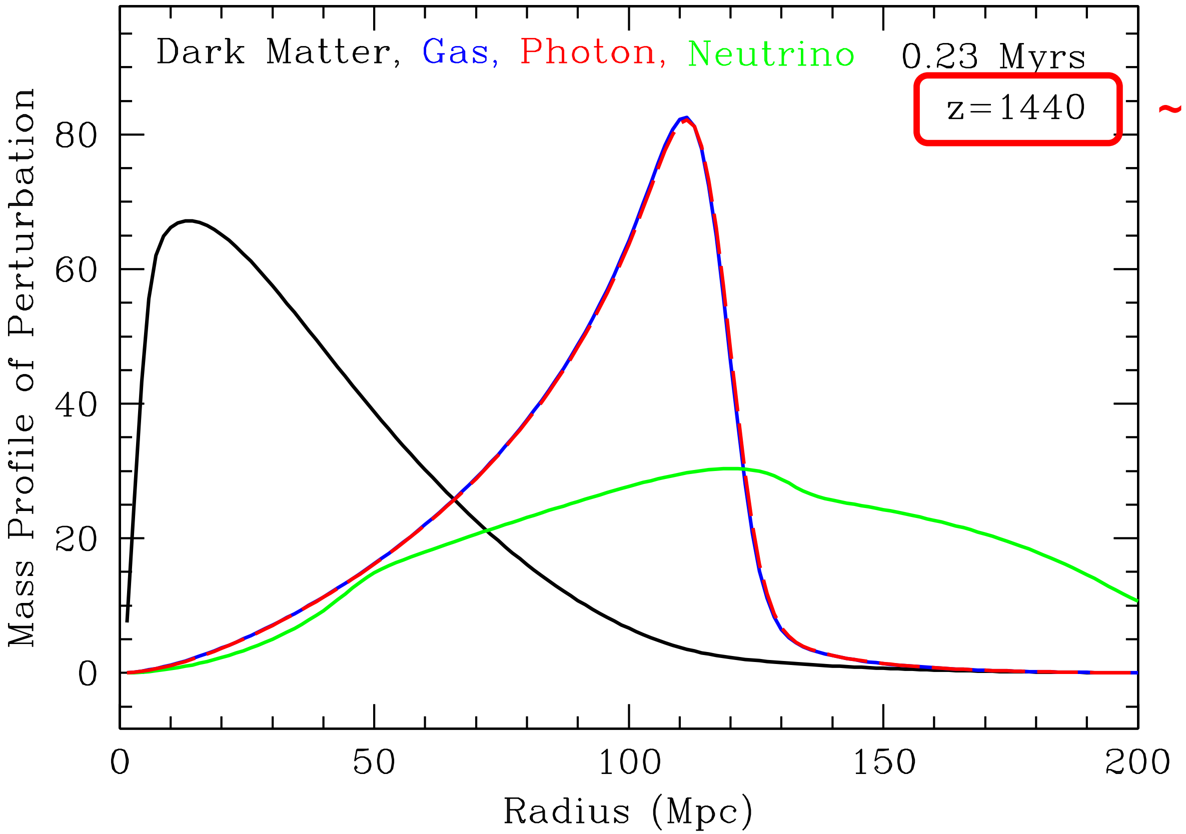
Eisenstein et al. (2007)

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



Eisenstein et al. (2007)

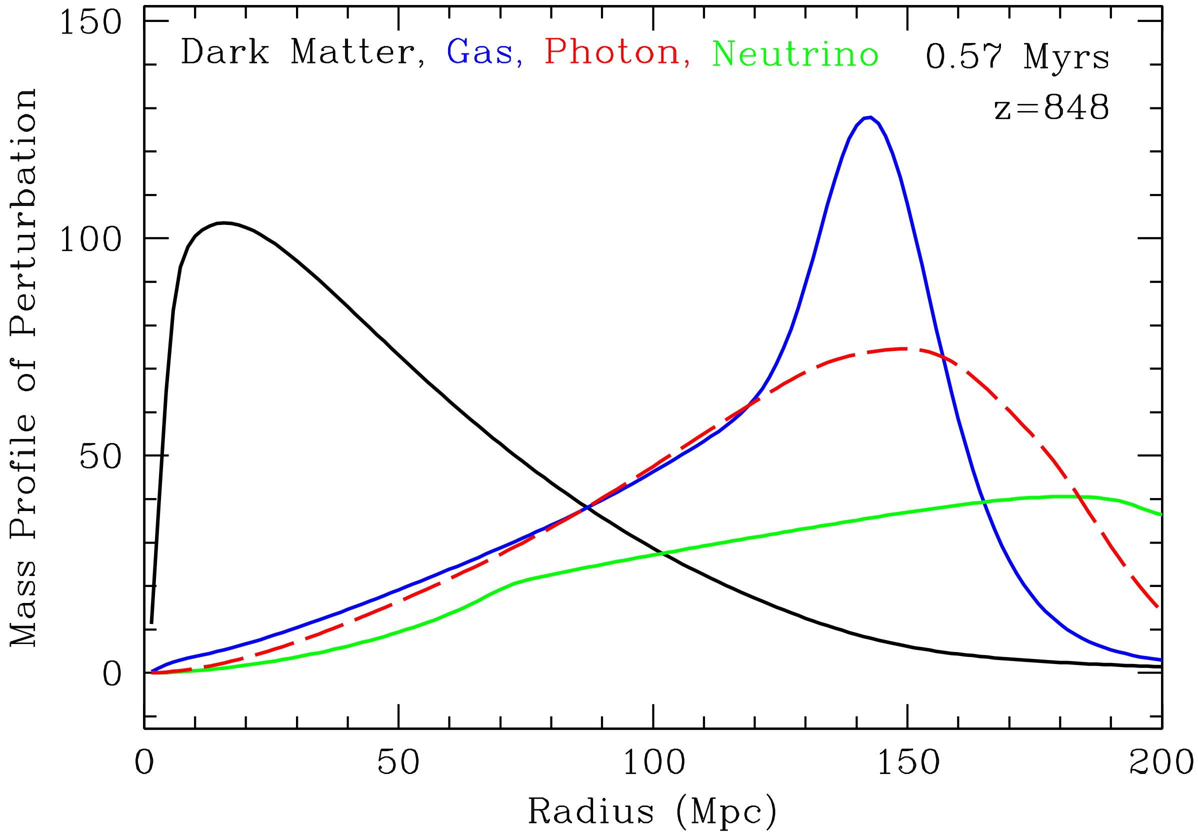
- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



~ recombination

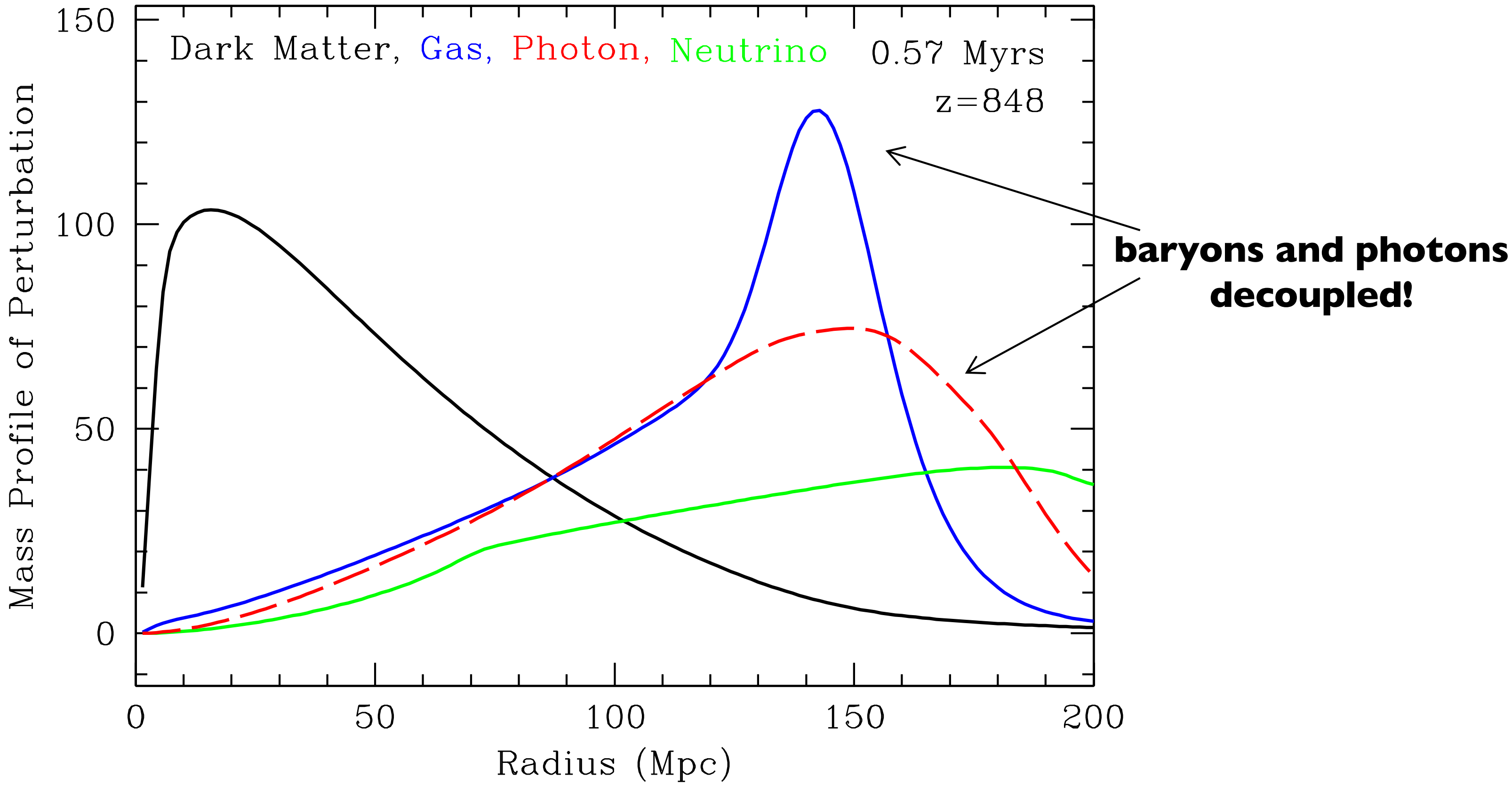
Eisenstein et al. (2007)

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



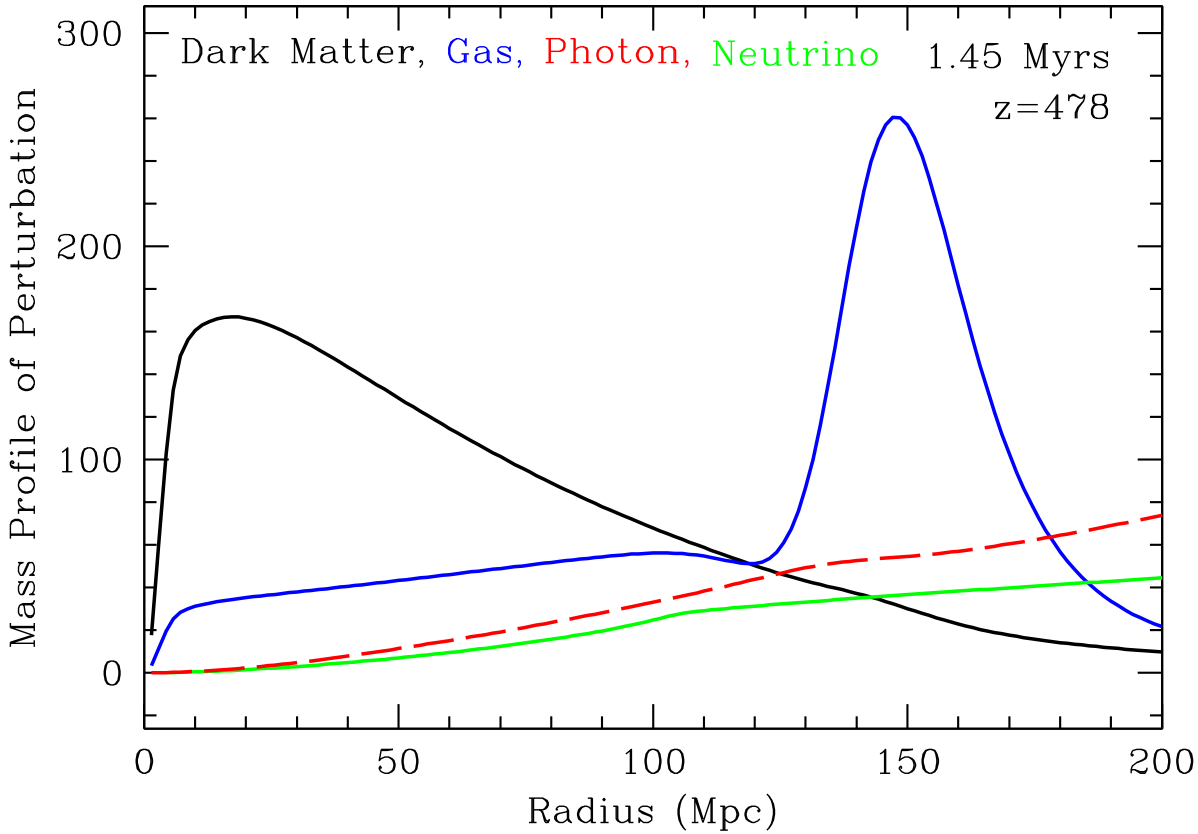
Eisenstein et al. (2007)

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



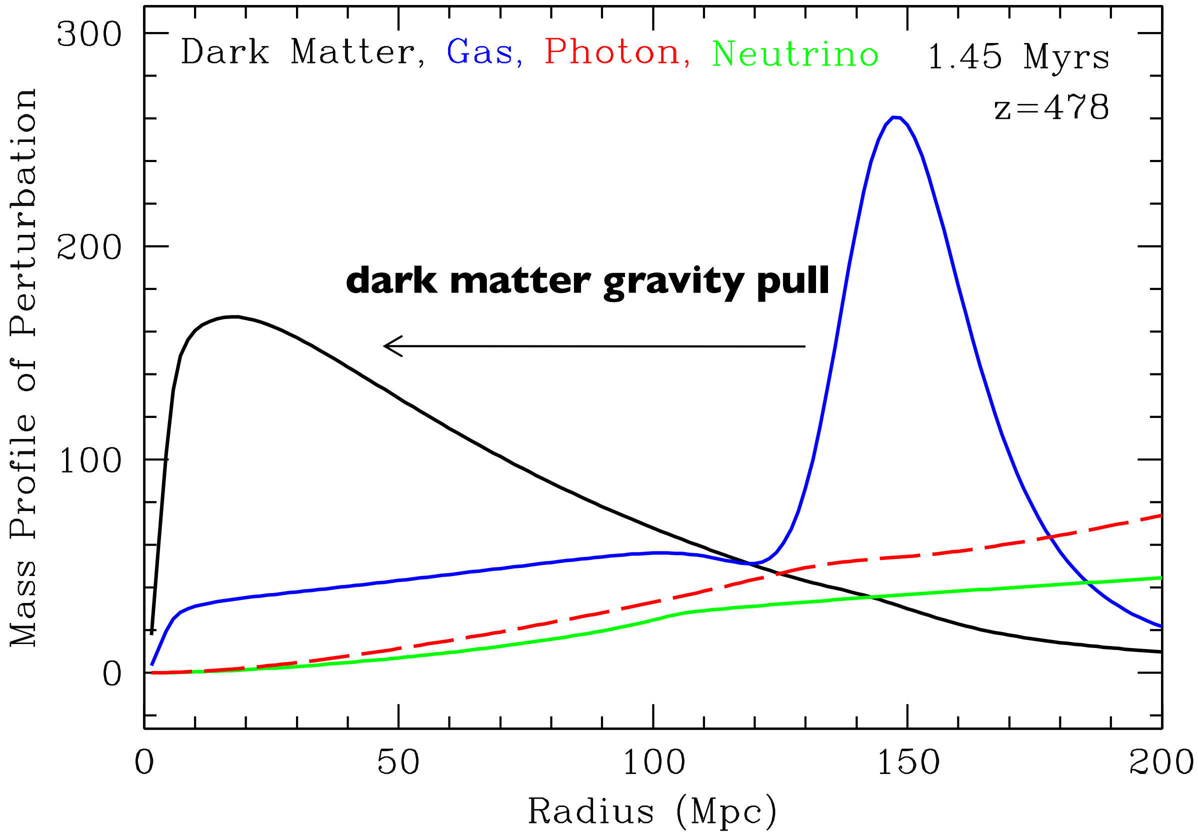
Eisenstein et al. (2007)

- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



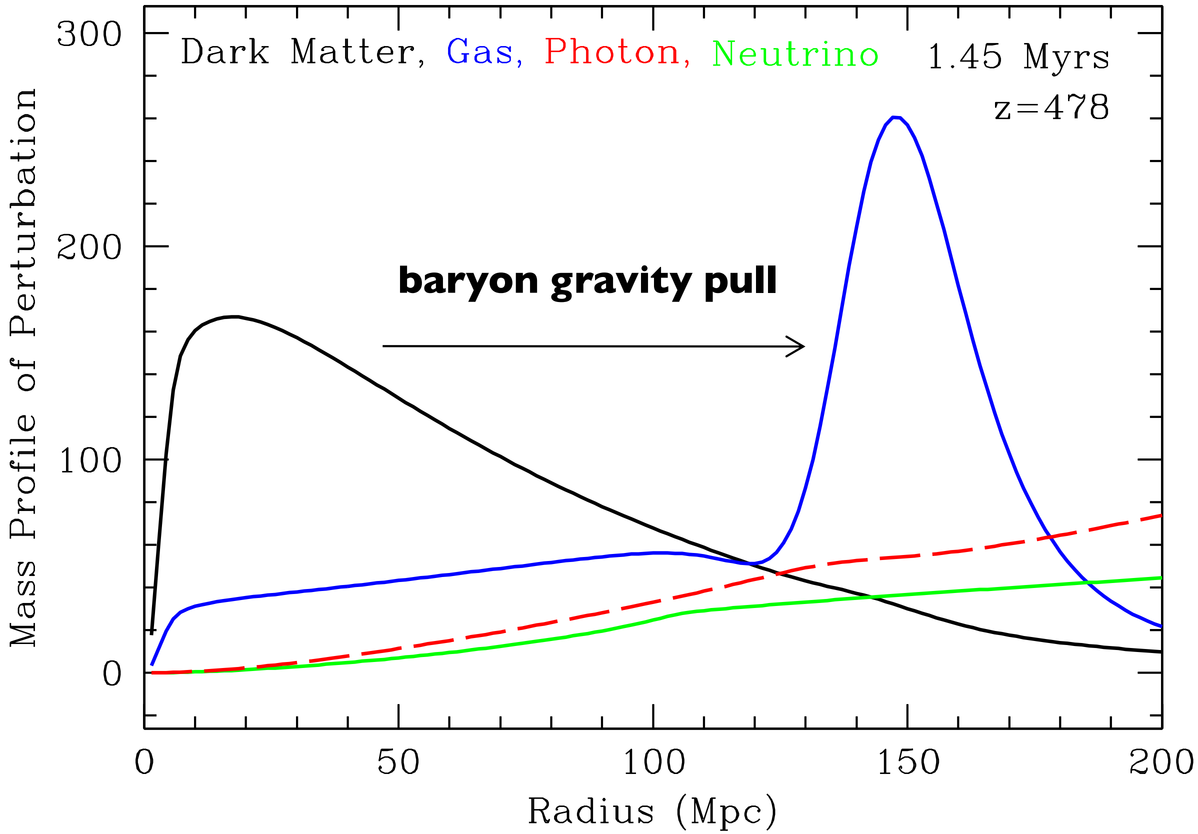
Eisenstein et al. (2007)

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



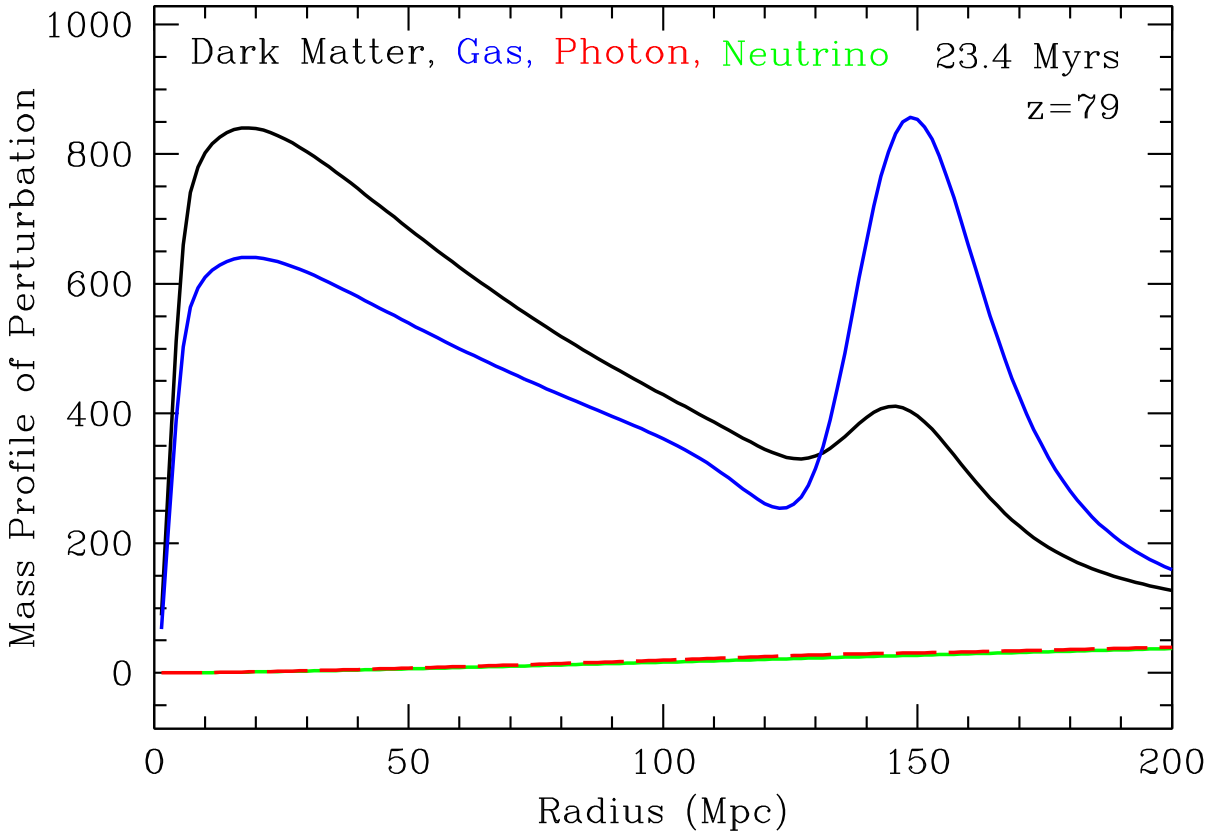
Eisenstein et al. (2007)

- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



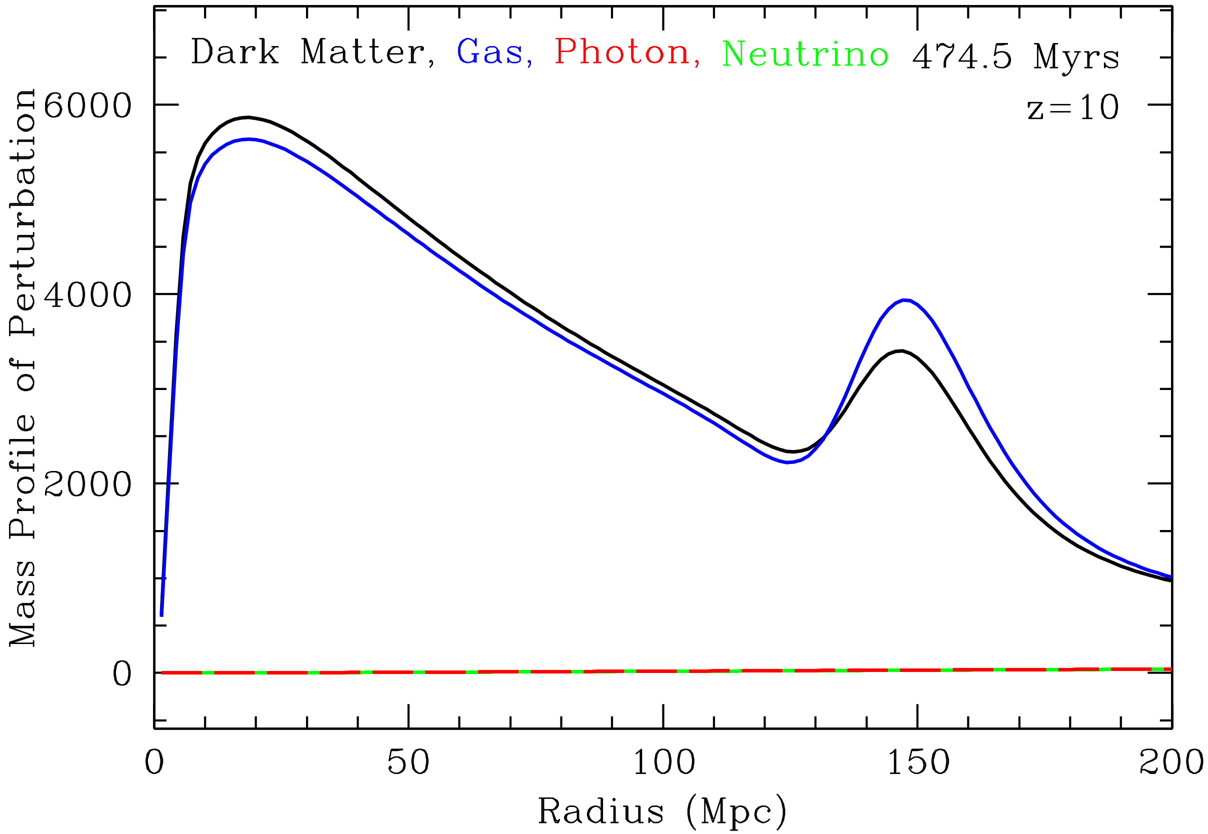
Eisenstein et al. (2007)

- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



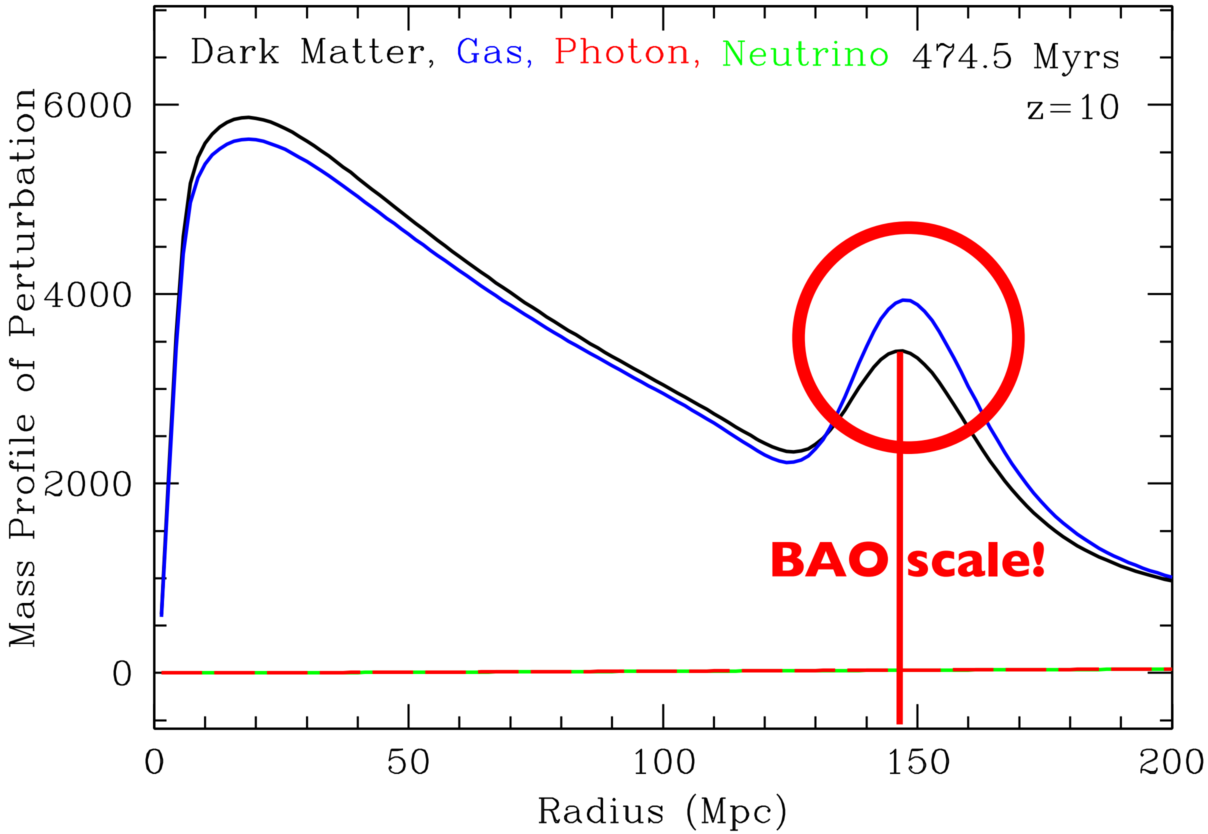
Eisenstein et al. (2007)

- baryonic acoustic oscillations
    - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



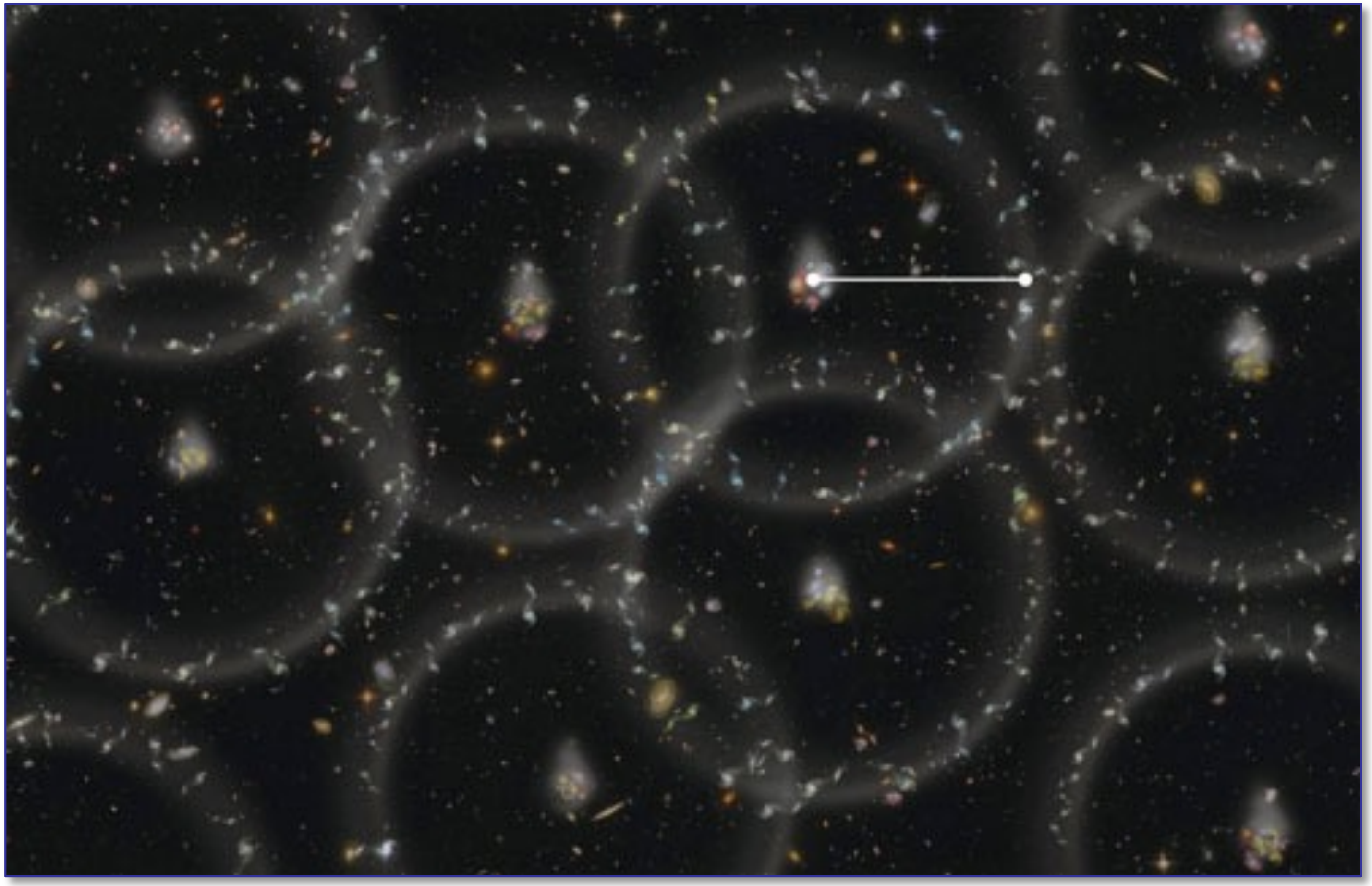
Eisenstein et al. (2007)

- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves

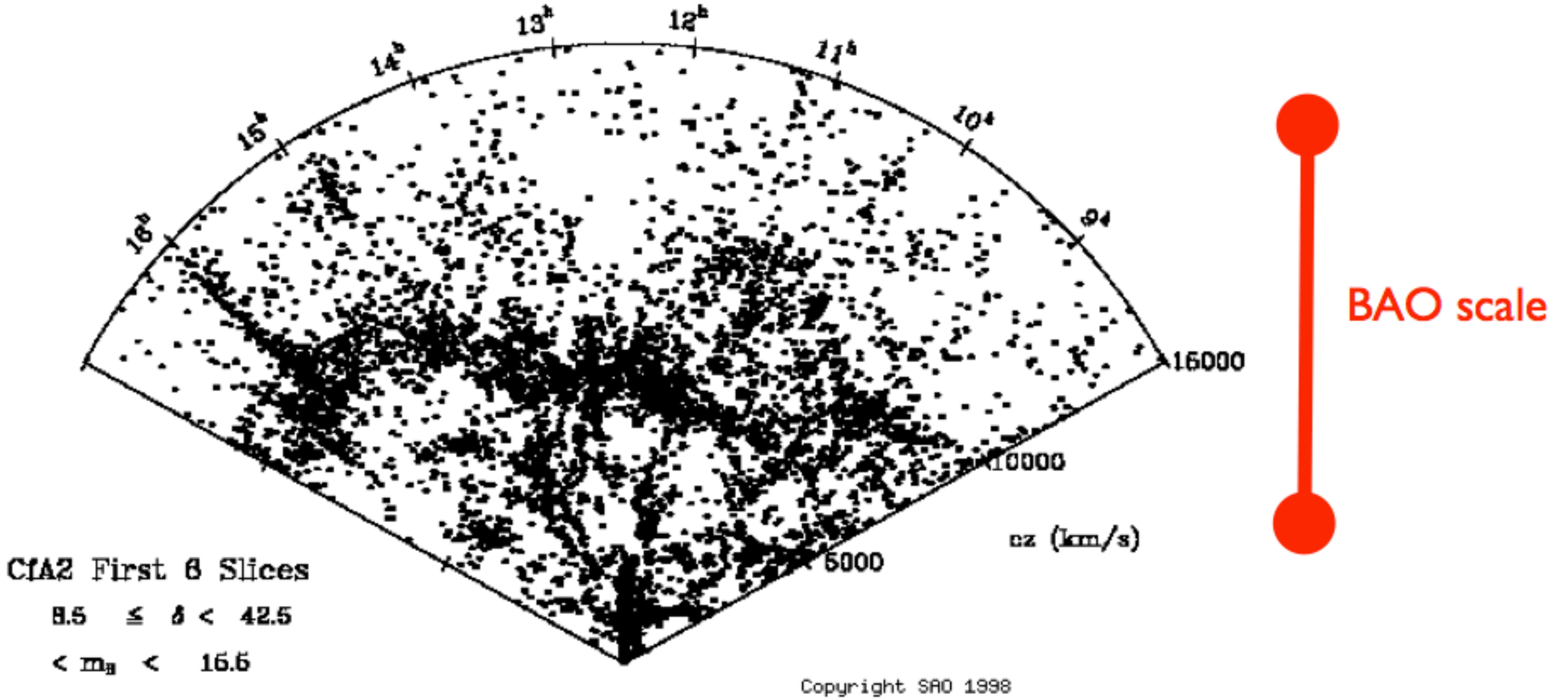


Eisenstein et al. (2007)

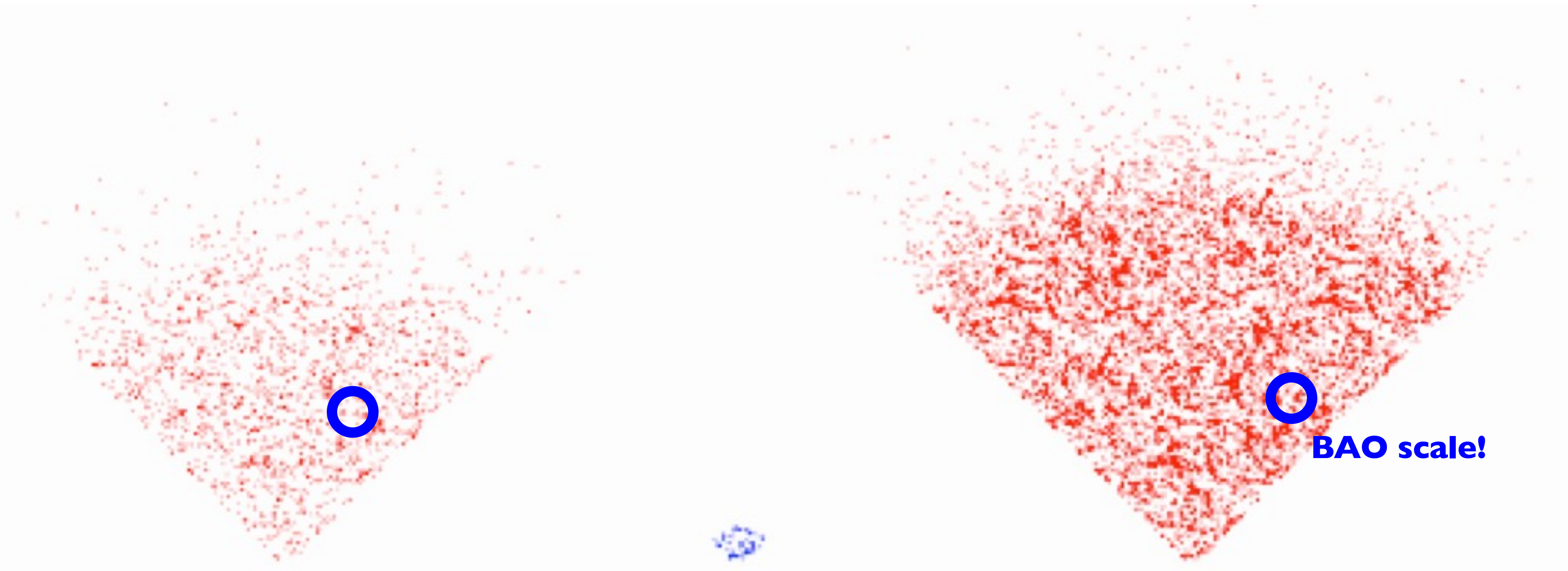
- baryonic acoustic oscillations
  - gravity vs. radiation pressure ➔ oscillations ➔ sound waves



- baryonic acoustic oscillations as a standard ruler
  - requirement for HUGE surveys

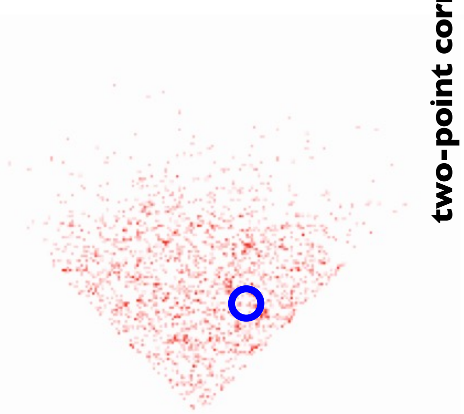


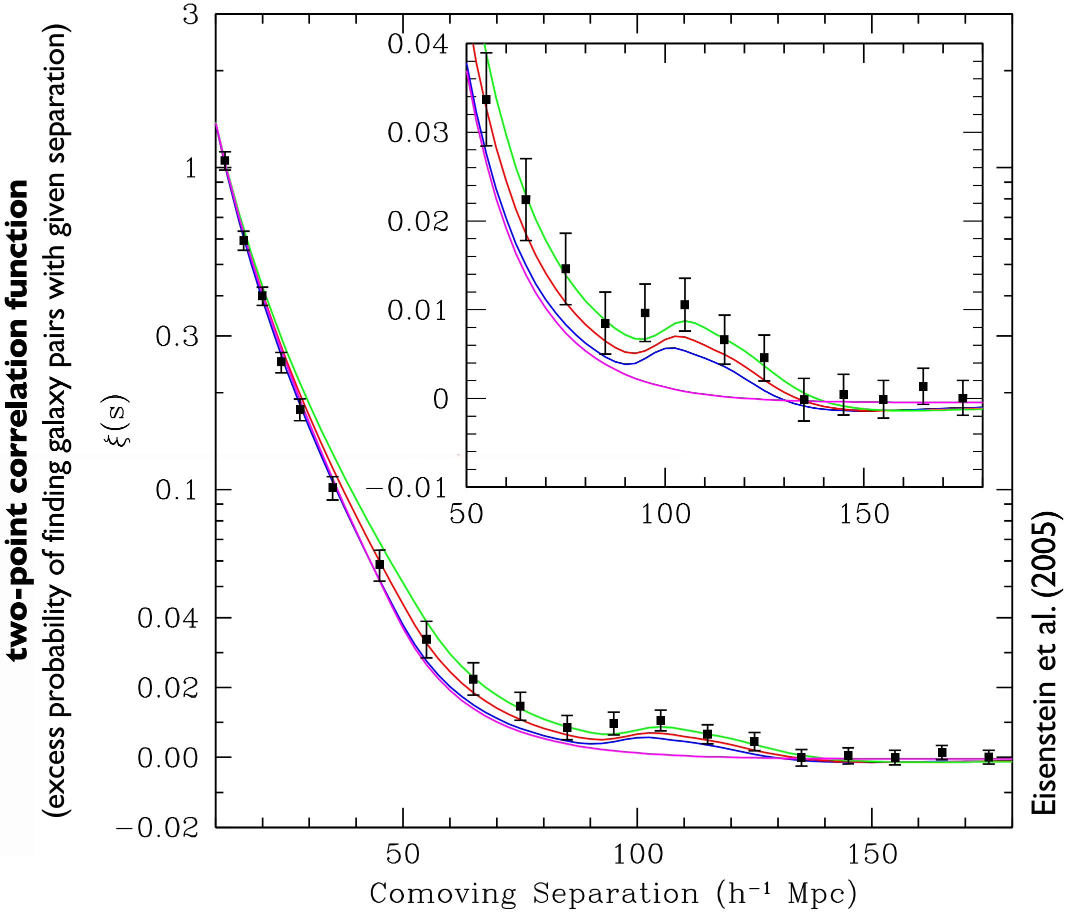
- baryonic acoustic oscillations as a standard ruler
    - requirement for HUGE surveys



SDSS CfA2 BOSS
(Baryon Oscillations Spectroscopic Survey)

- baryonic acoustic oscillations as a standard ruler
  - discovered in SDSS survey in 2005


SDSS



- intrinsic fluctuations – where do they come from?

- intrinsic fluctuations – where do they come from?

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\rho_m}{\rho_m}$$

(adiabatic fluctuations)

- intrinsic fluctuations – where do they come from?

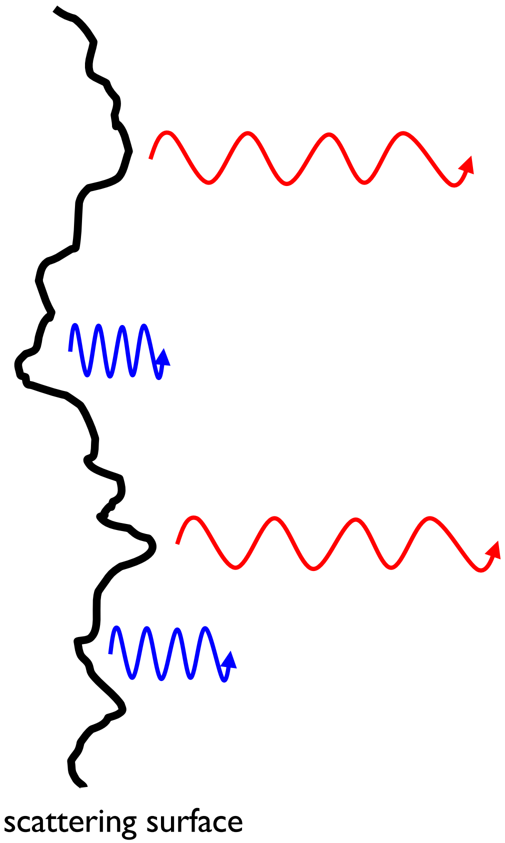
$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\rho_m}{\rho_m}$$ (adiabatic fluctuations)

- more detailed calculations:
  - Sachs-Wolfe effect
  - Doppler effect
  - Silk damping

- Sachs-Wolfe effect
  - variations in gravitational potential lead to temperature fluctuations

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta \Phi}{c^2}$$

$$\Delta\theta \approx 10^{\circ}$$

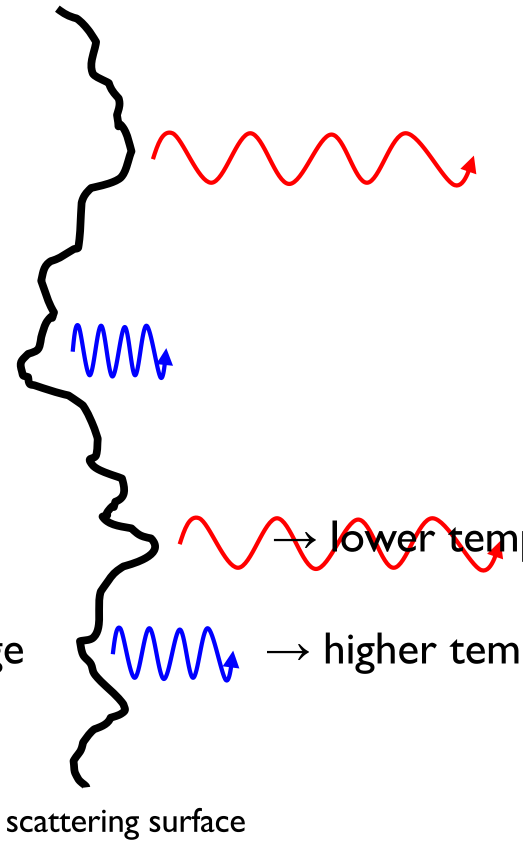


- Sachs-Wolfe effect

  - variations in gravitational potential lead to temperature fluctuations

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta \Phi}{c^2}$$

$$\Delta\theta \approx 10^{\circ}$$



dark matter over-density = potential well → energy loss → lower temperature

dark matter under-density = potential hill → no energy change → higher temperature

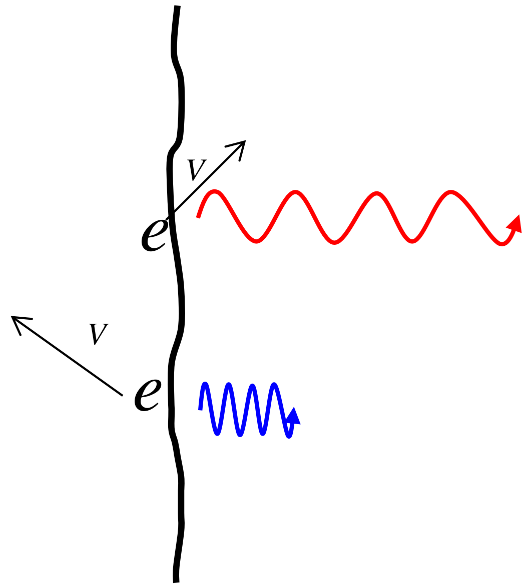
(+ time dilation!)

(effect dominates on super-horizon scales…)

- Doppler effect
  - last-scattering electrons have finite velocity

$$\frac{\delta T}{T} = -\frac{\vec{V} \cdot \vec{n}}{c}$$

$$\Delta\theta \approx 1^{\circ}$$

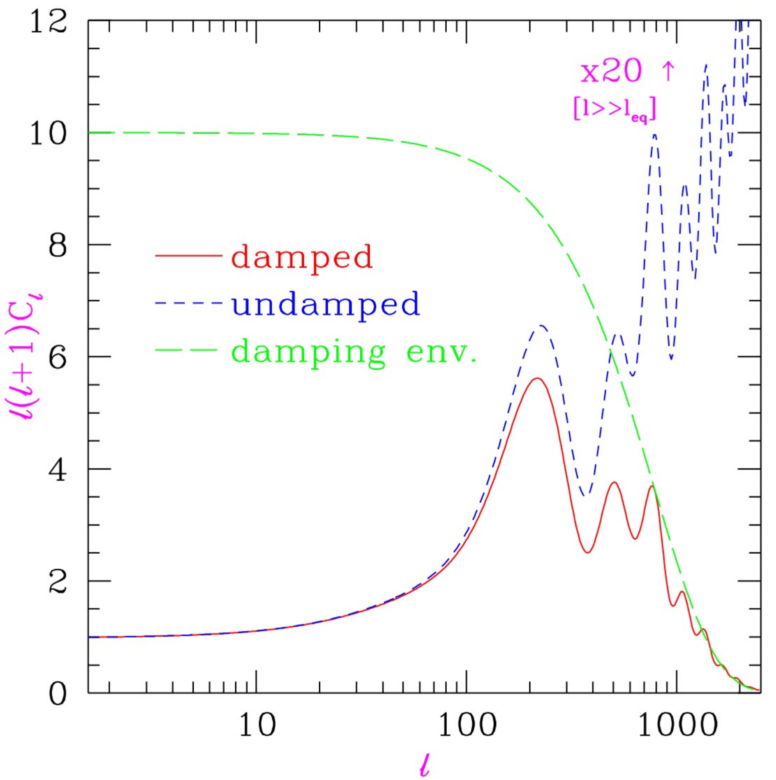


last scattering surface

- Silk damping

  - photon diffusion from high to low-density regions
  - electrons are dragged along via Compton interactions
  - protons also follow due to Coulomb coupling to electrons

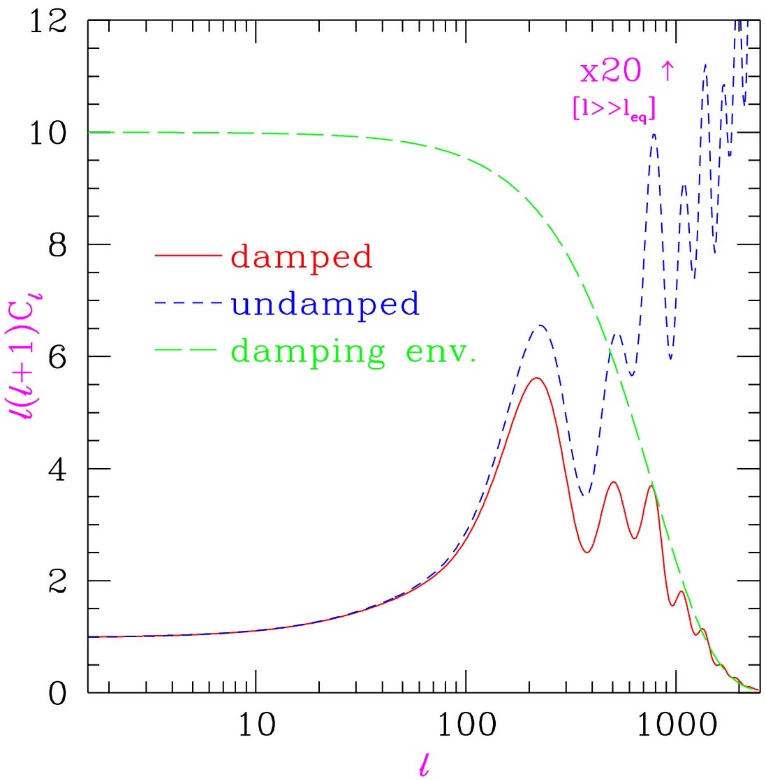
$\rightarrow$ baryonic density fluctuations are damped! $\left(\Delta\theta << 1^{\circ}\right)$



- Silk damping

  - photon diffusion from high to low-density regions
  - electrons are dragged along via Compton interactions
  - protons also follow due to Coulomb coupling to electrons

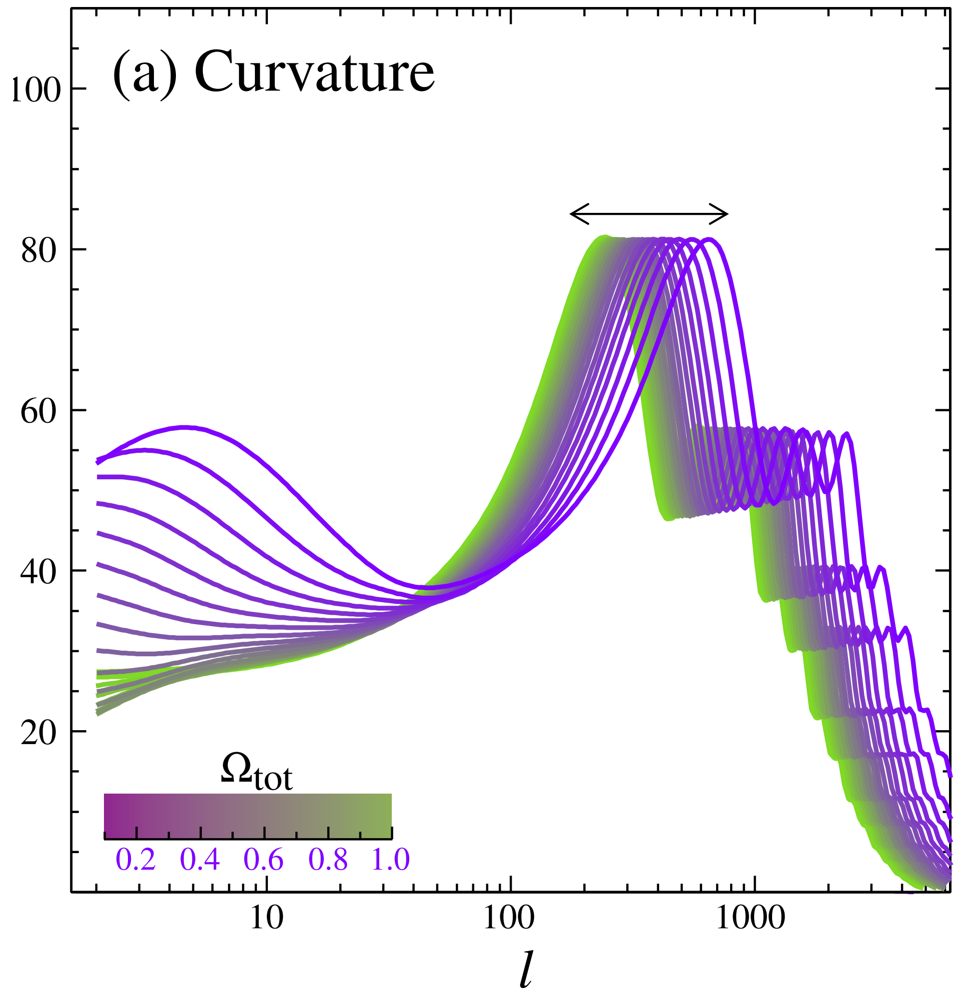
$\rightarrow$ baryonic density fluctuations are damped!



sensitive to baryon content!

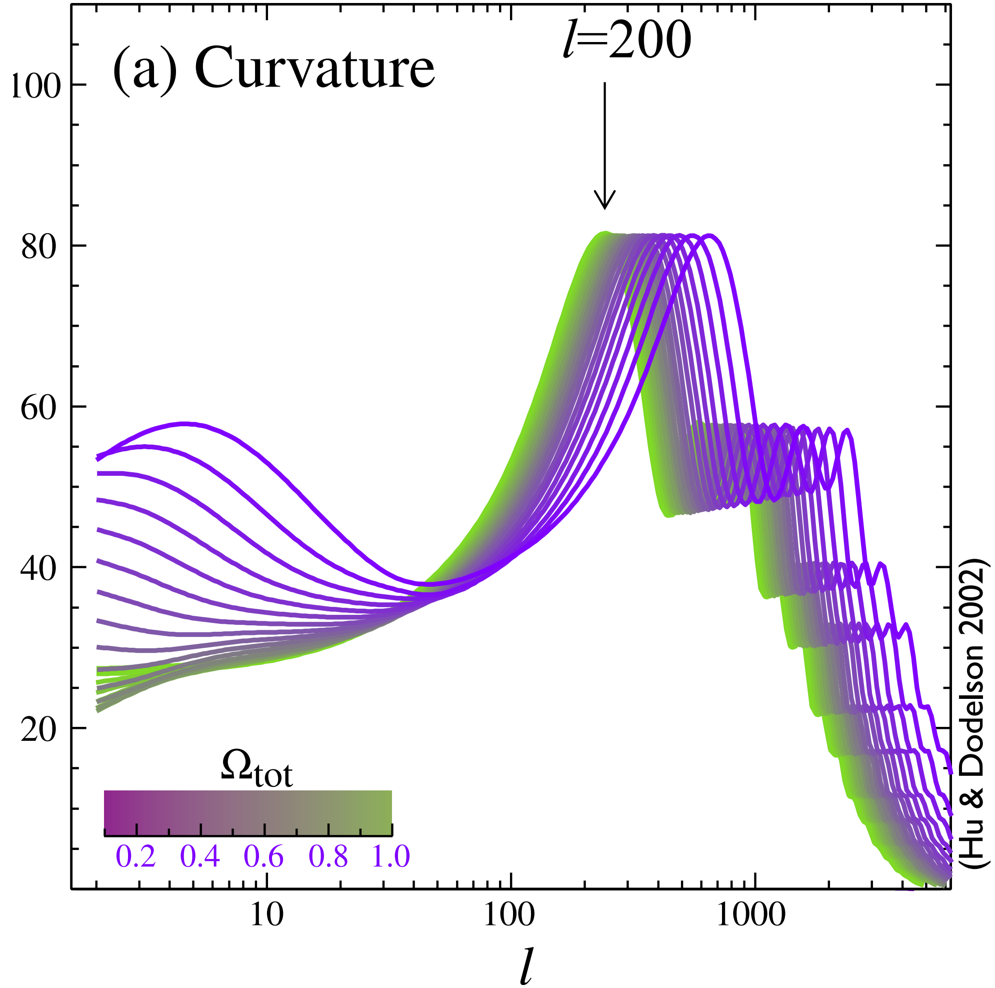
- discovery
- origin
- **CMB fluctuations**
  - primary (created during inflation):
    - intrinsic fluctuations
    - how to quantify them?
    - what's their nature?
    - **sensitivity to cosmological parameters?**
  - secondary (created after photon decoupling):
    - what's their nature?
    - what's their importance?

- sensitivity to cosmic parameters
  - curvature



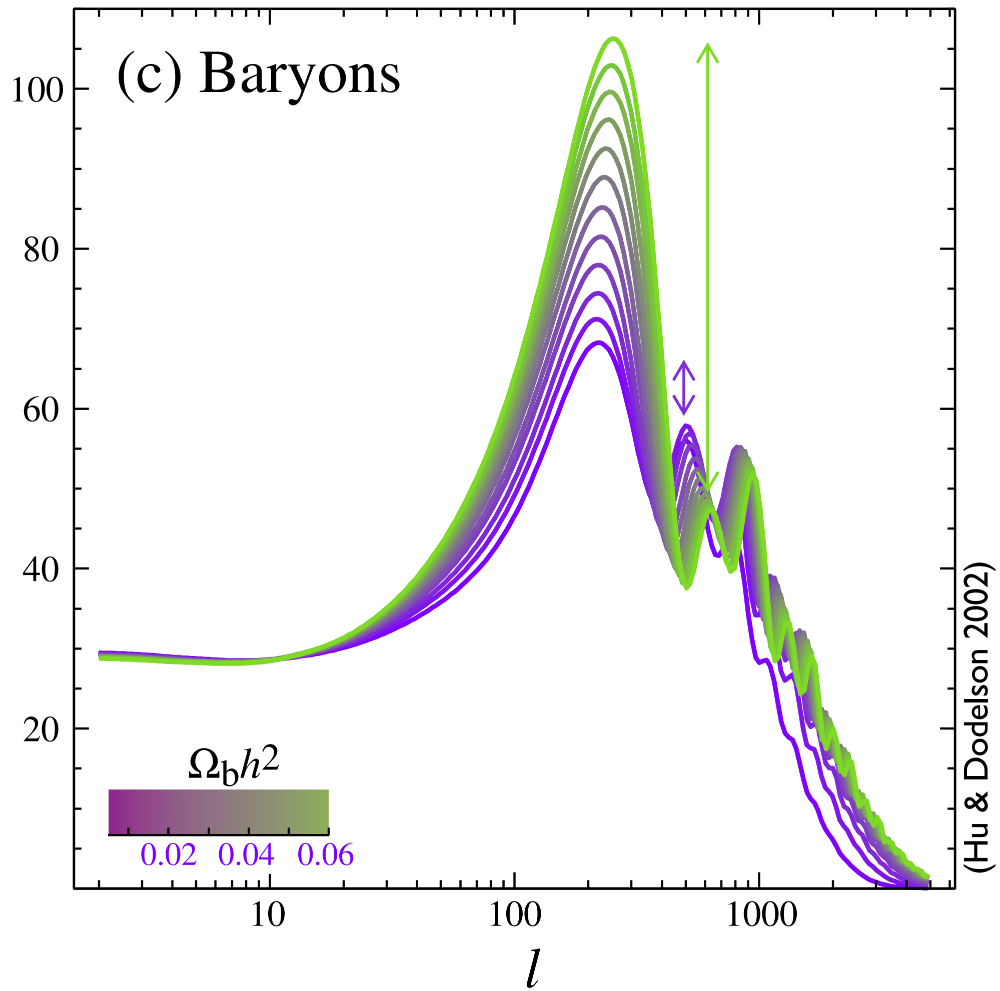
(Hu & Dodelson 2002)

- sensitivity to cosmic parameters
  - curvature



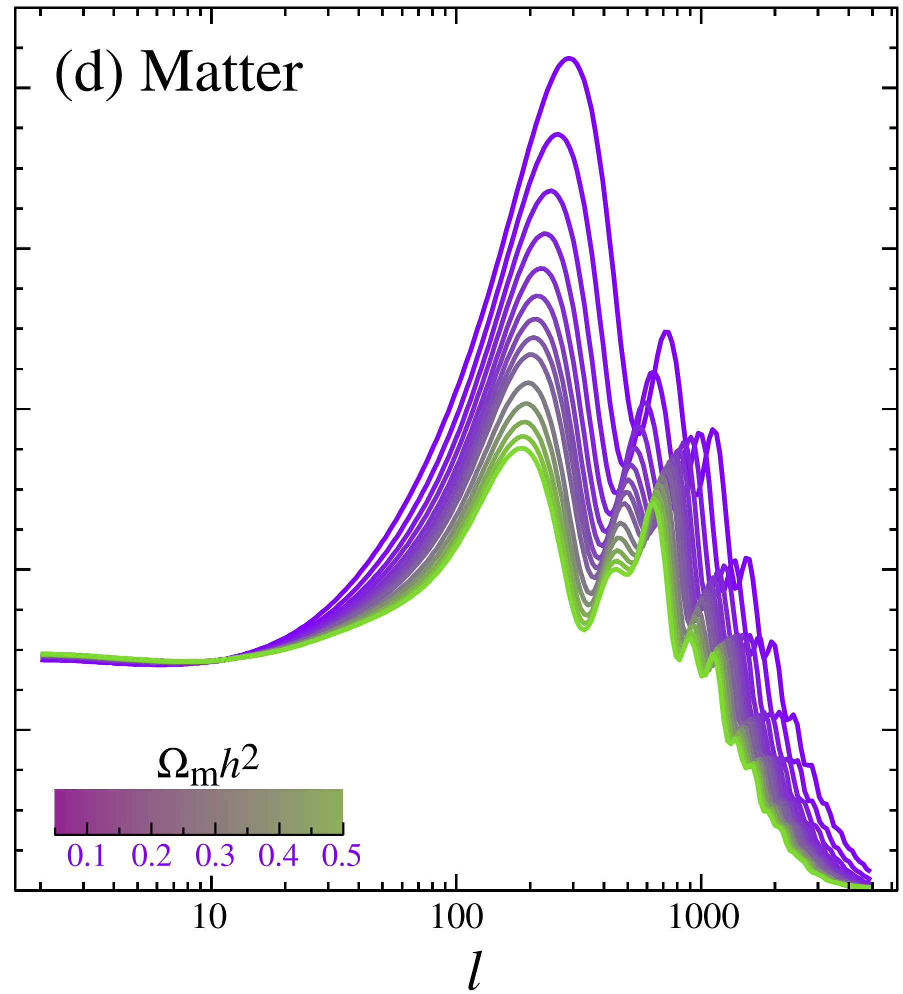
first peak at $l \sim 200$ => Universe is spatially flat!

- sensitivity to cosmic parameters
    - matter content – baryons



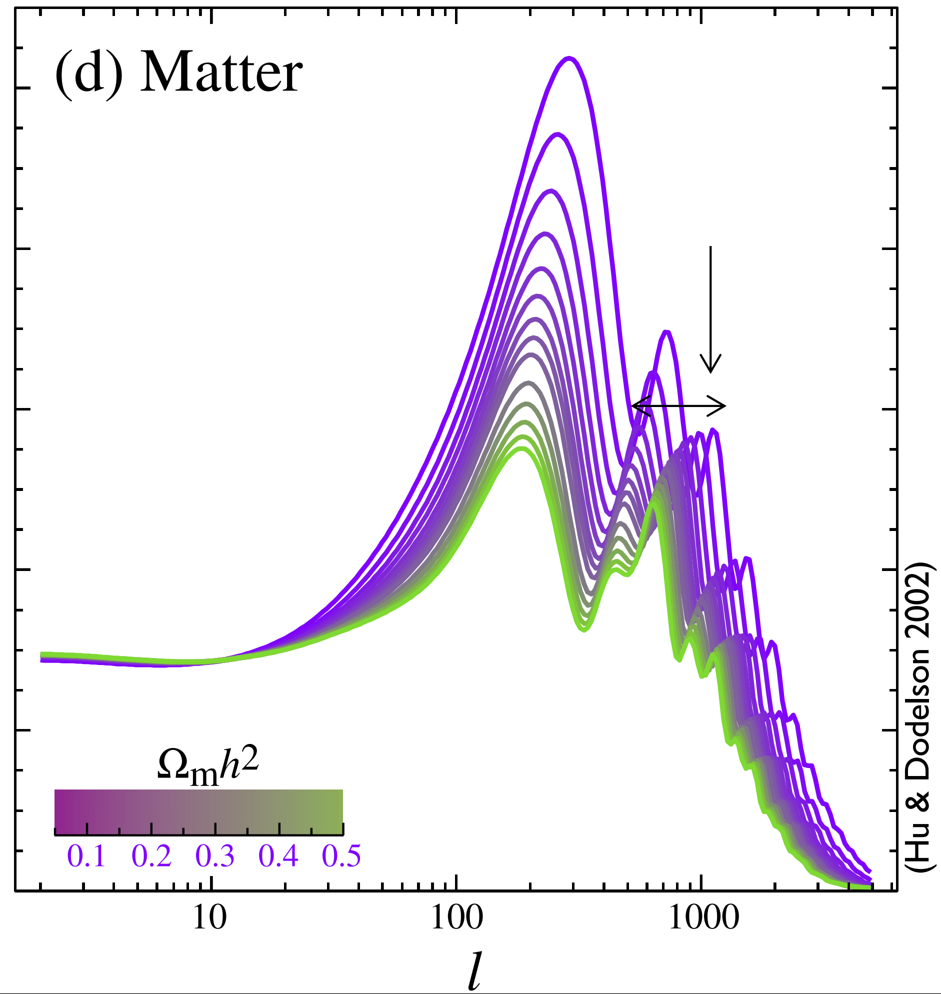
ratio of 1st to 2nd peak => $\Omega_b h^2 \sim 0.02$

- sensitivity to cosmic parameters
  - matter content – all matter



(Hu & Dodelson 2002)

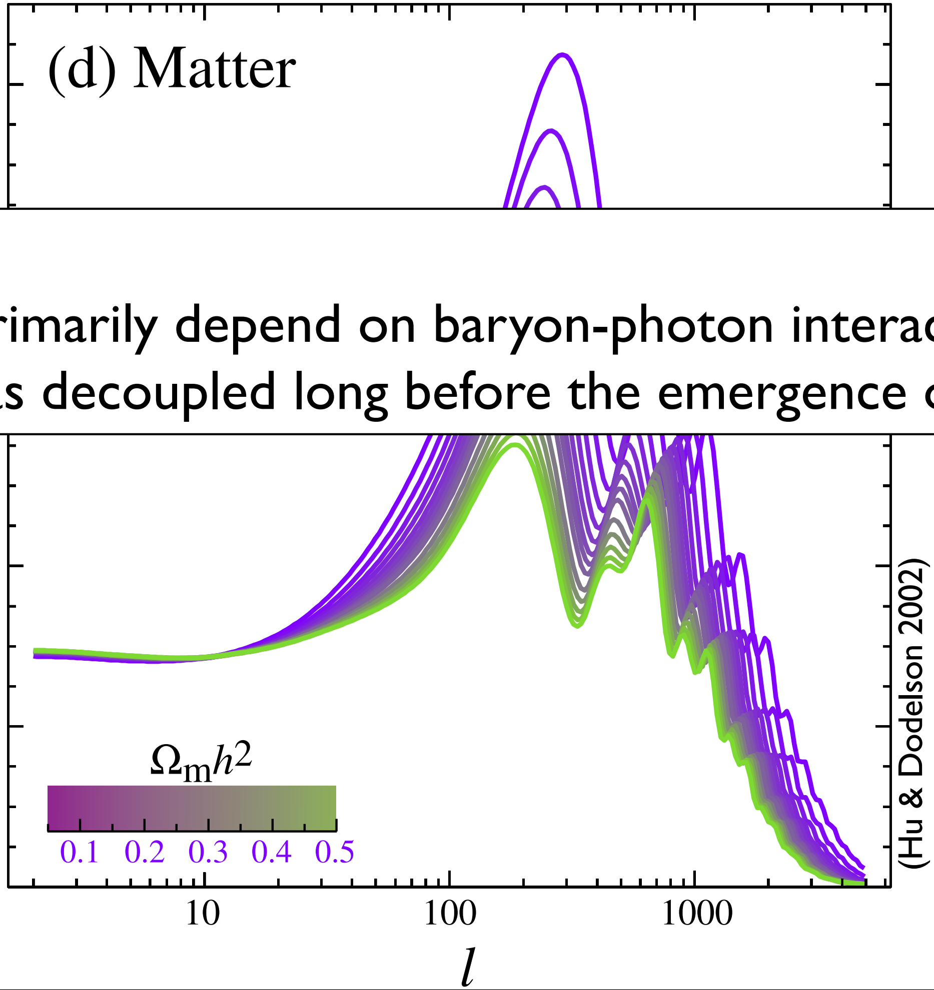
- sensitivity to cosmic parameters
  - matter content – all matter



third peak separates dark matter from baryons => $\Omega_m h^2 \sim 0.3$

- sensitivity to cosmic parameters

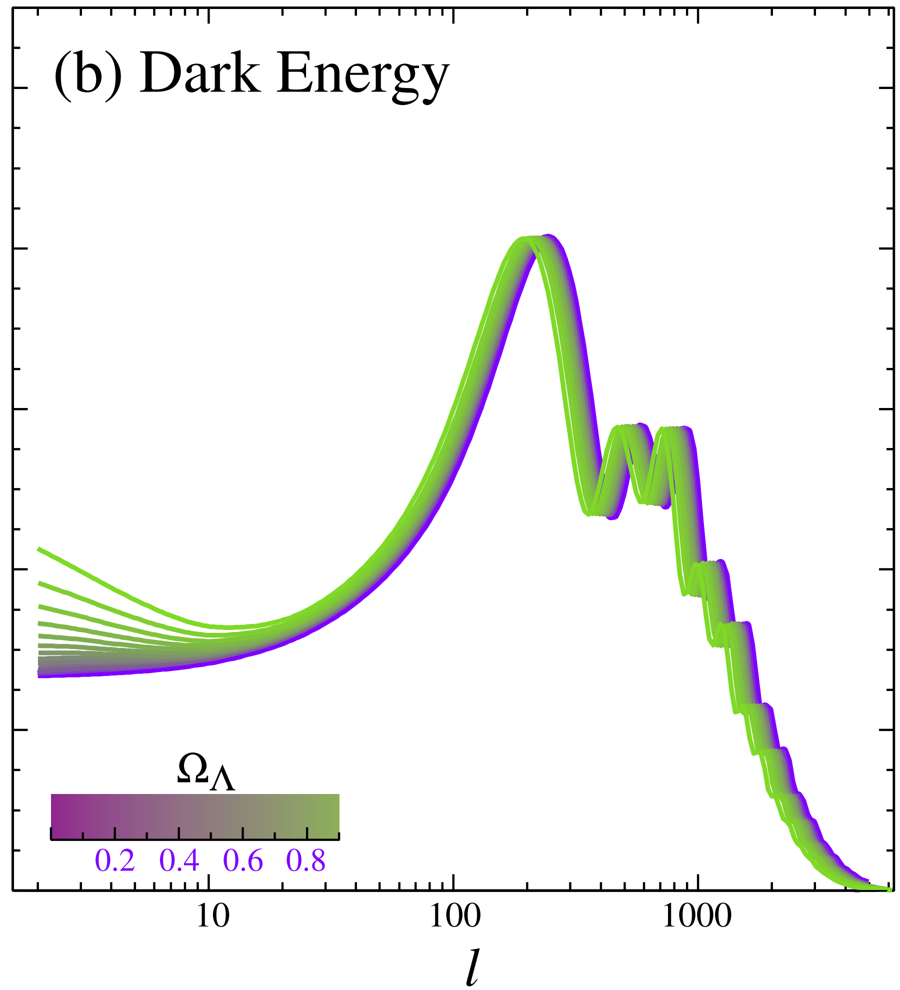
  - matter content – all matter



Note:
- anisotropies primarily depend on baryon-photon interactions/ratio
- dark matter has decoupled long before the emergence of the anisotropies

third peak separates dark matter from baryons => $\Omega_m h^2 \sim 0.3$

- sensitivity to cosmic parameters
  - matter content – dark energy



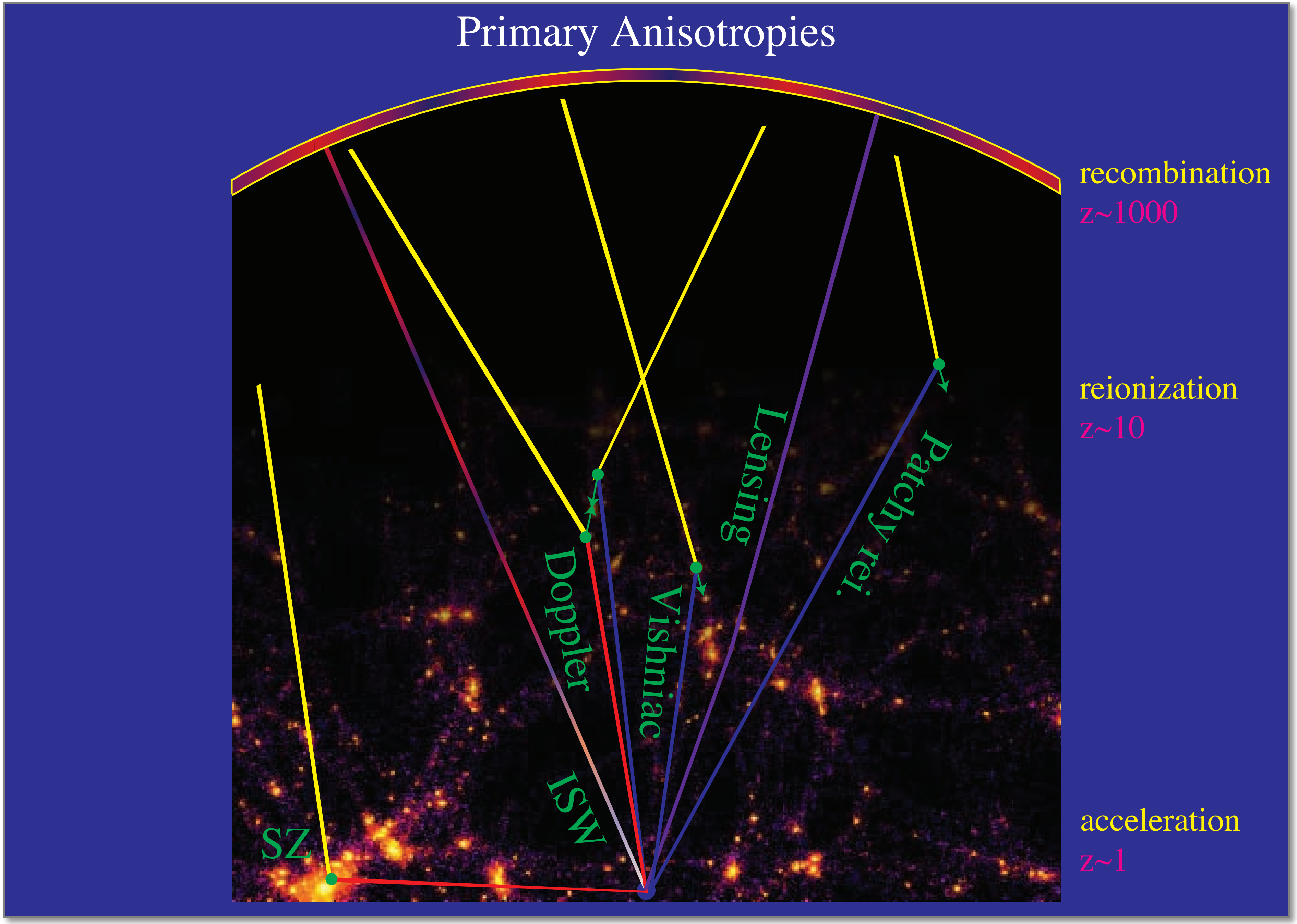
(Hu & Dodelson 2002)

- sensitivity to cosmic parameters

the shape of the power spectrum
of the intrinsic temperature fluctuations in the CMB
depends sensitively on the cosmological parameters!

- discovery
- origin
- **CMB fluctuations**
  - primary (created during inflation):
    - intrinsic fluctuations
    - how to quantify them?
    - what's their nature?
    - sensitivity to cosmological parameters?
  - <u>secondary</u> (created after photon decoupling):
    - **what's their nature?**
    - what's their importance?

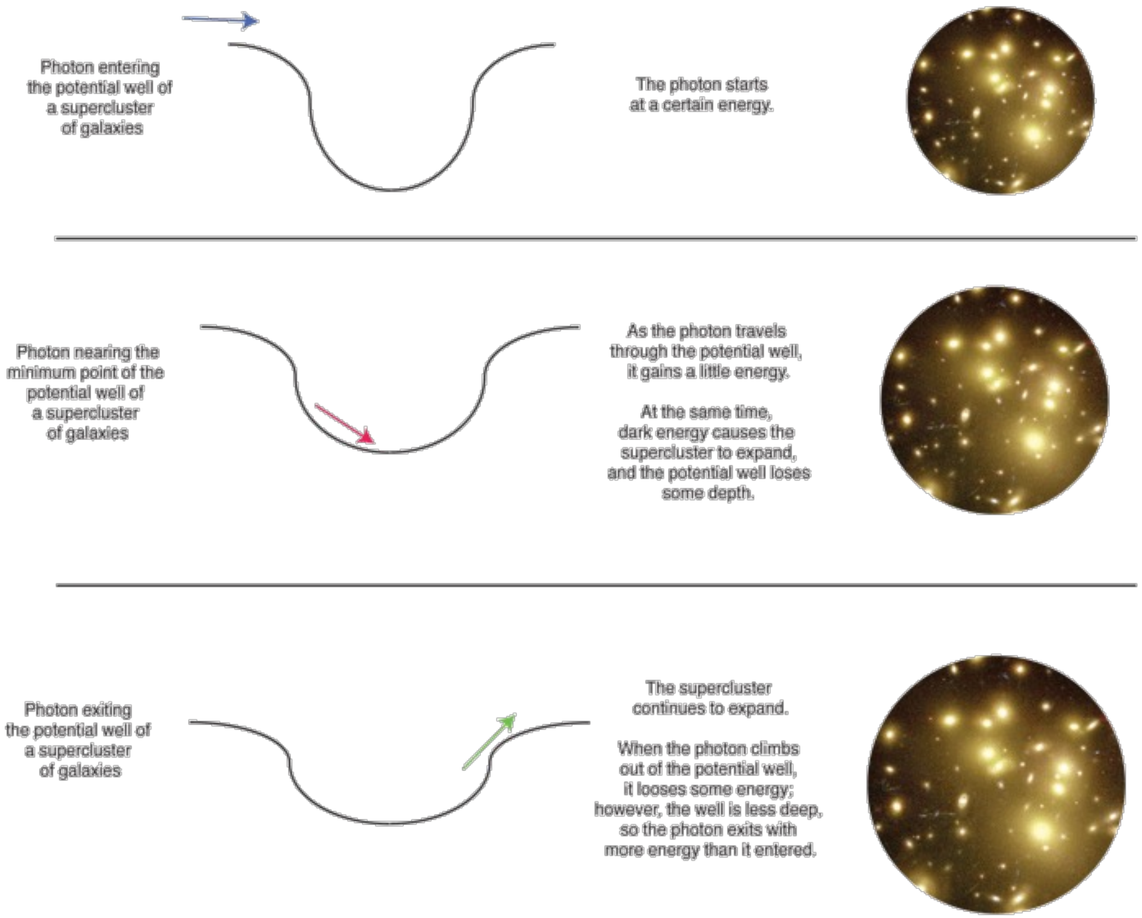
interactions of CMB photons with matter inbetween z_{dec} and $z=0$



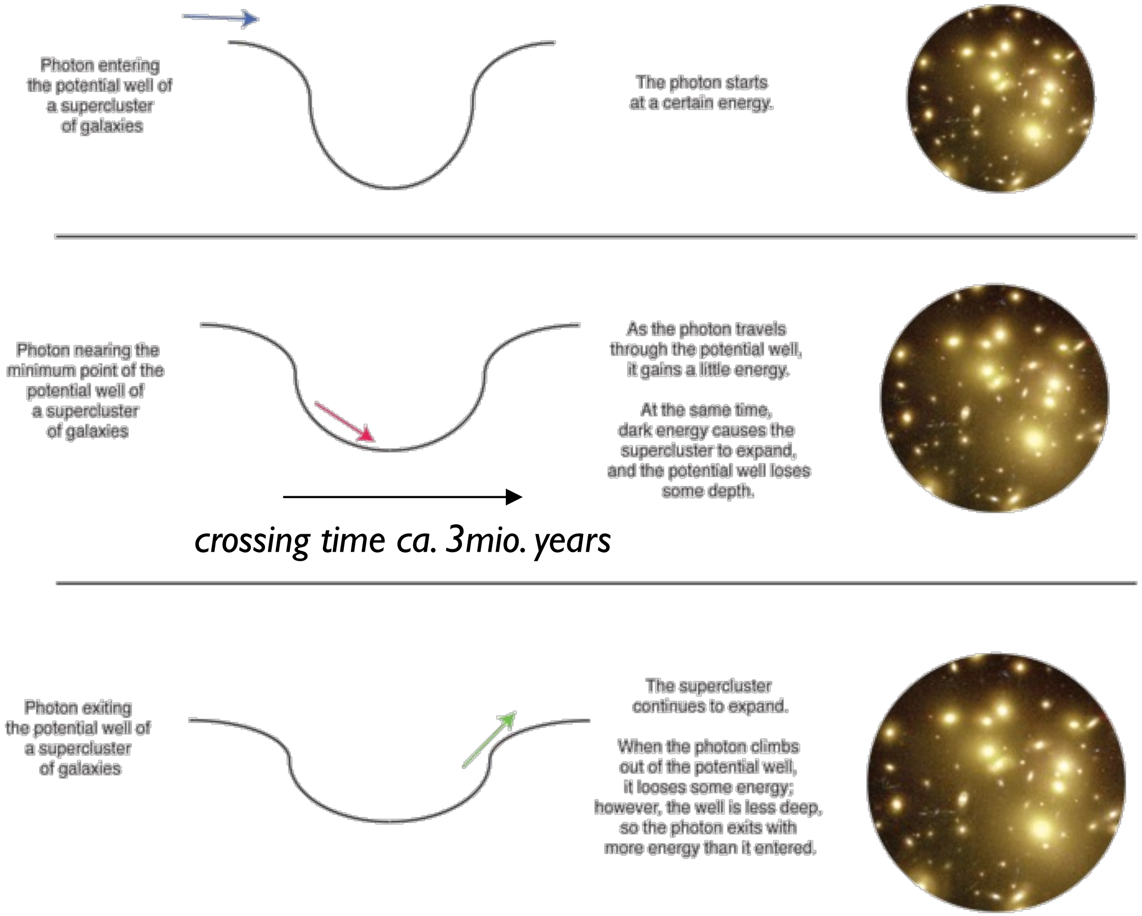
(Wayne Hu Lecture)

- secondary fluctuations – where do they come from?
  - integrated Sachs-Wolfe effect
  - Rees-Sciama effect
  - Sunyaev-Zeldovich effect (thermal & kinematic)
  - Ostriker-Vishniac effect
  - patchy reionisation of the Universe
  - gravitational lensing

- integrated Sachs-Wolfe (ISW) effect
  - fluctuations due to **global** (time-varying) gravitational potential
  - caused by time-varying linear perturbations (e.g. superclusters)

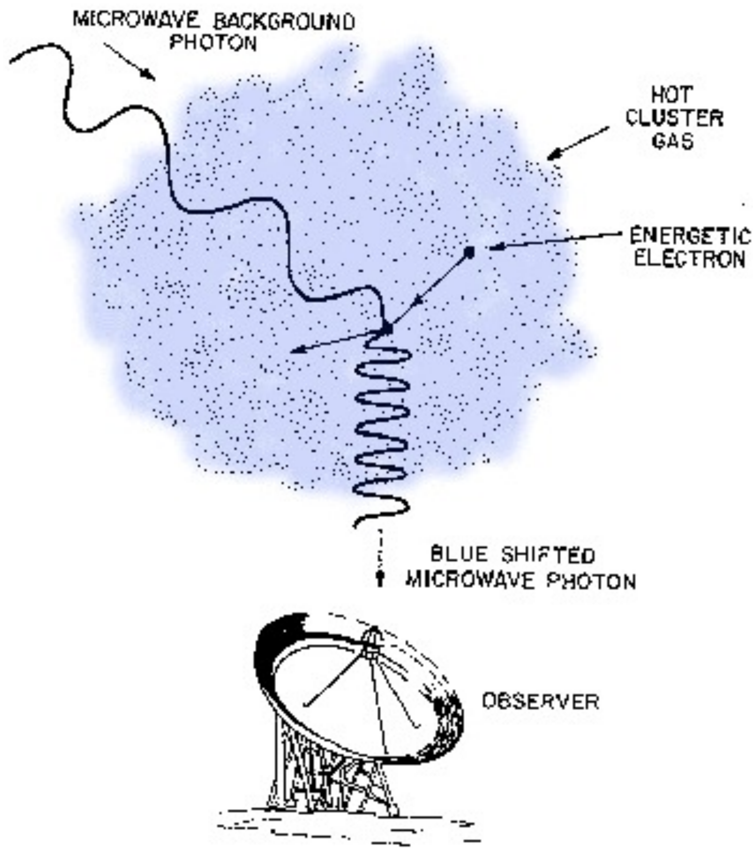


- integrated Sachs-Wolfe (ISW) effect
    - fluctuations due to **global** (time-varying) gravitational potential
    - caused by time-varying linear perturbations (e.g. superclusters)



- Rees-Sciama (RS) effect
  - fluctuations due to **local** (time-varying) gravitational potential
  - caused by time-varying non-linear perturbations (e.g. haloes)

- Sunyaev-Zeldovich (SZ) effect



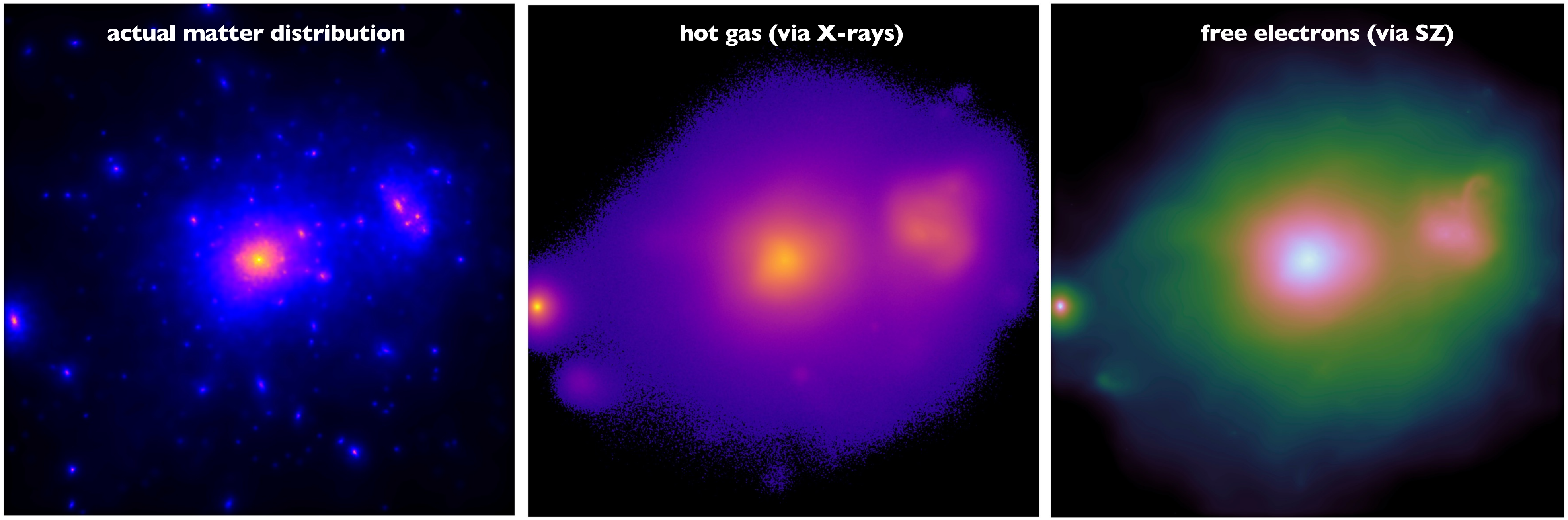
- Sunyaev-Zeldovich (SZ) effect

  - thermal: CMB photons scatter off the hot intra-cluster gas

  - kinetic: the cluster gas has a bulk motion with respects to the CMB and hence induces a Doppler shift

- Sunyaev-Zeldovich (SZ) effect
  - thermal: CMB photons scatter off the hot intra-cluster gas
  - kinetic: the cluster gas has a bulk motion with respects to the CMB and hence induces a Doppler shift

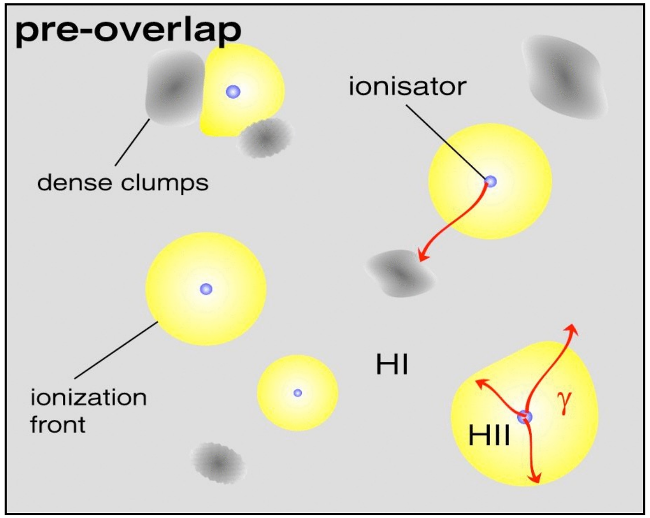
the SZ effect is used to study galaxy clusters:



- Ostriker-Vishniac (OV) effect

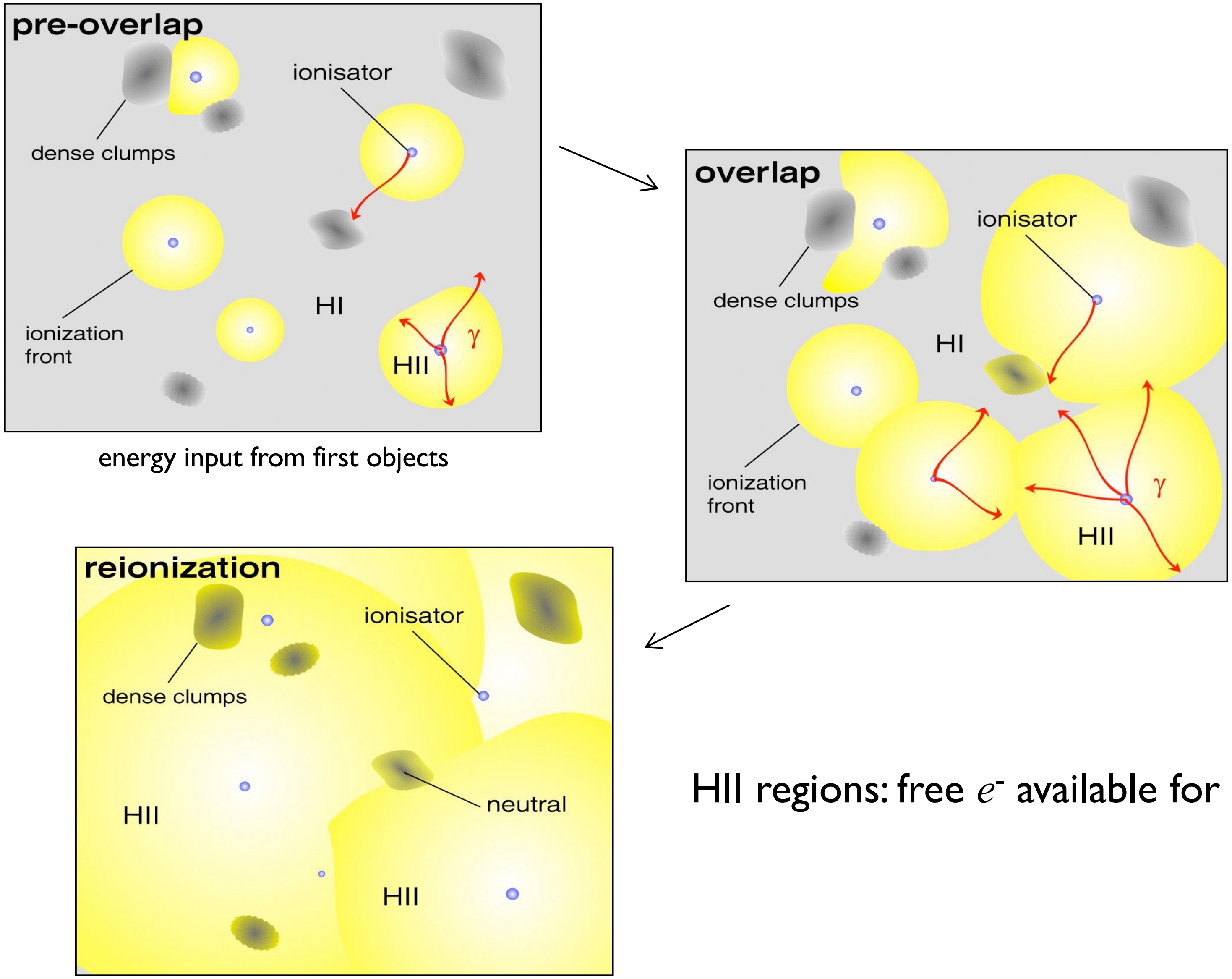
  - higher order coupling between bulk flow of electrons and their density perturbations (outside virialized objects)

- patchy re-ionisation of the Universe



energy input from first objects

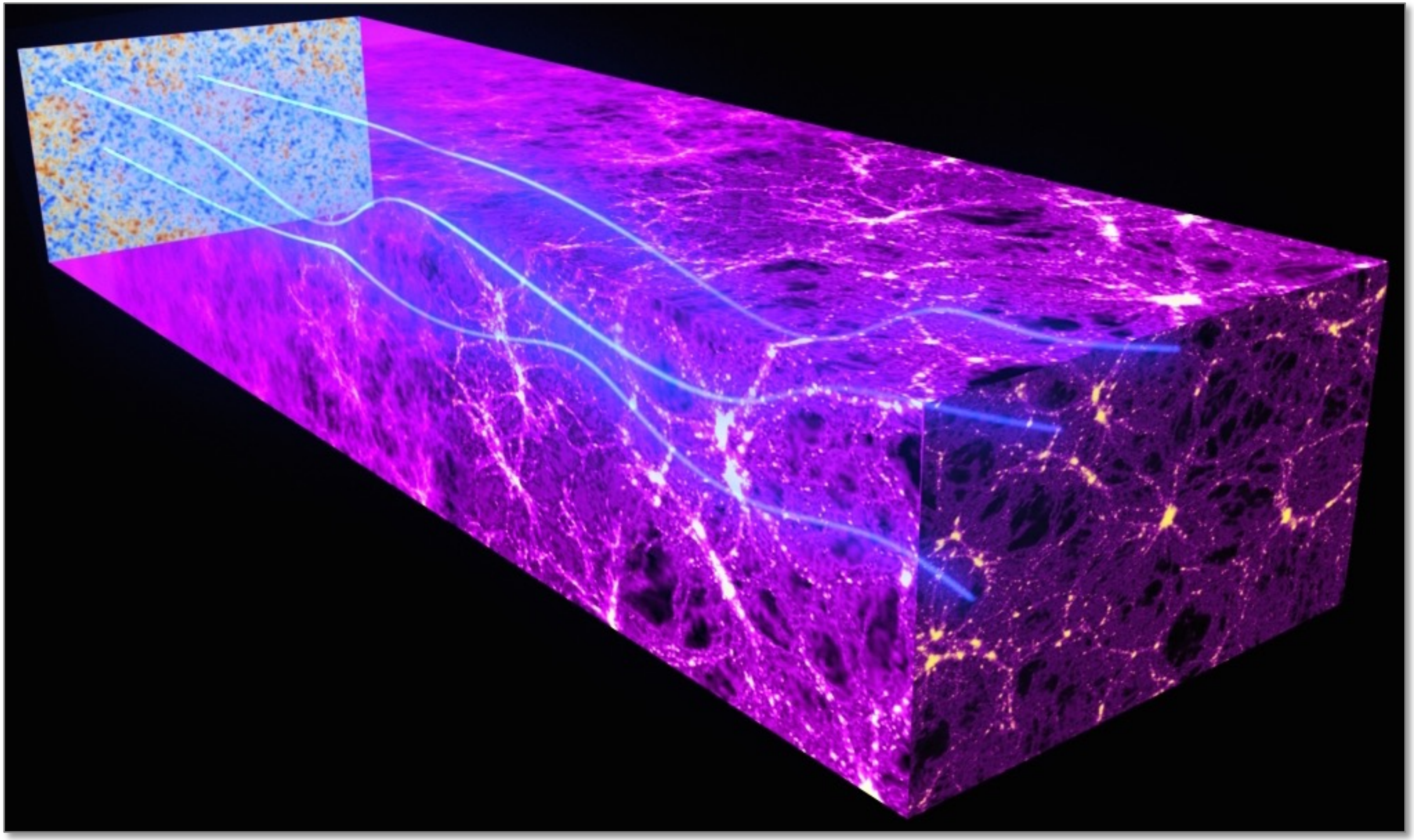
- patchy re-ionisation of the Universe



energy input from first objects

HII regions: free e^- available for scattering!

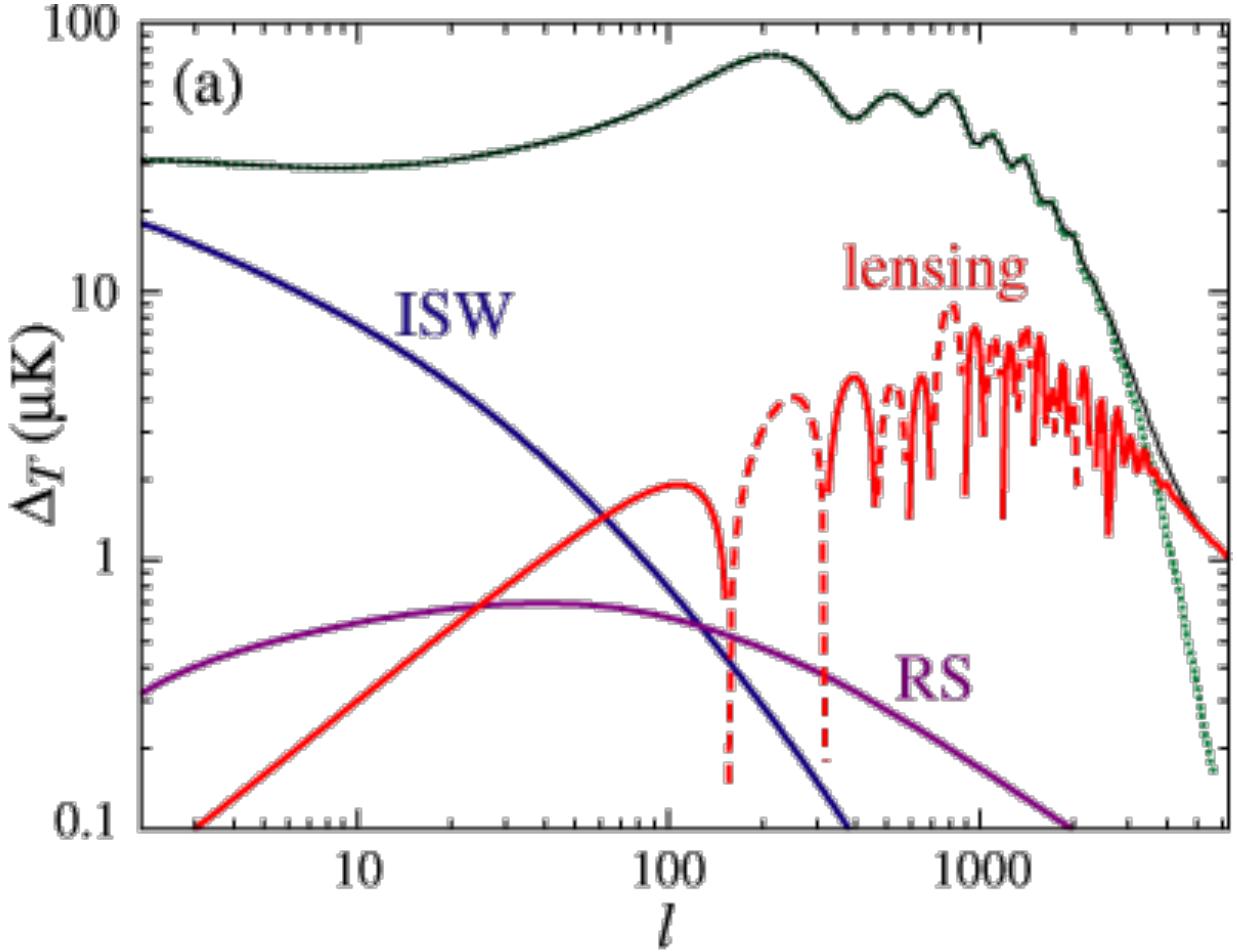
- gravitational lensing



(ESA, http://sci.esa.int/planck/51606-gravitational-lensing-of-the-cosmic-microwave-background/)

- discovery
- origin
- **CMB fluctuations**
  - primary (created during inflation):
    - intrinsic fluctuations
    - how to quantify them?
    - what's their nature?
    - sensitivity to cosmological parameters?
  - <u>secondary</u> (created after photon decoupling):
    - what's their nature?
    - **what's their importance?**

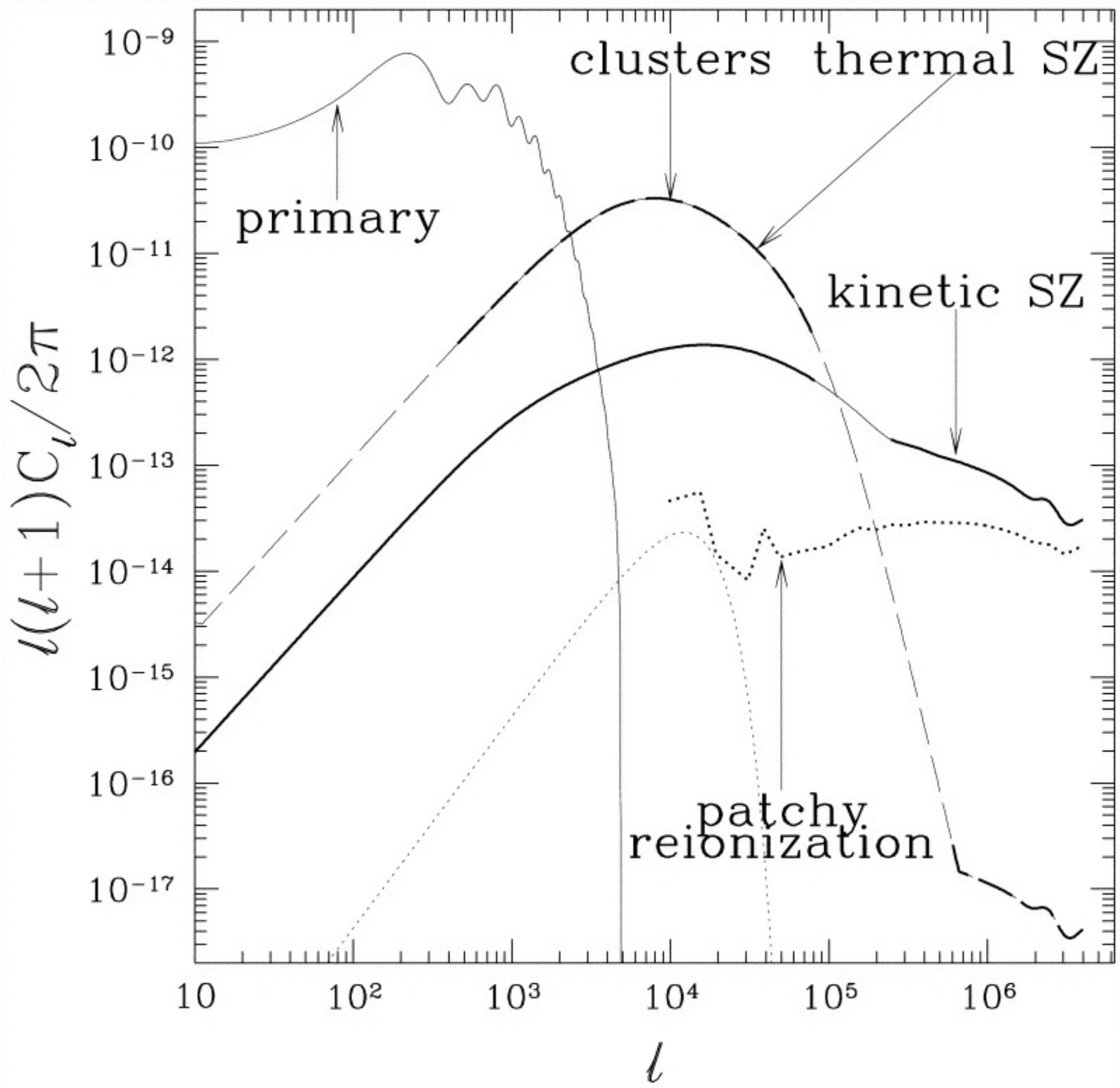
- relevance of secondary effects



(Hu & Dodelson 2002)

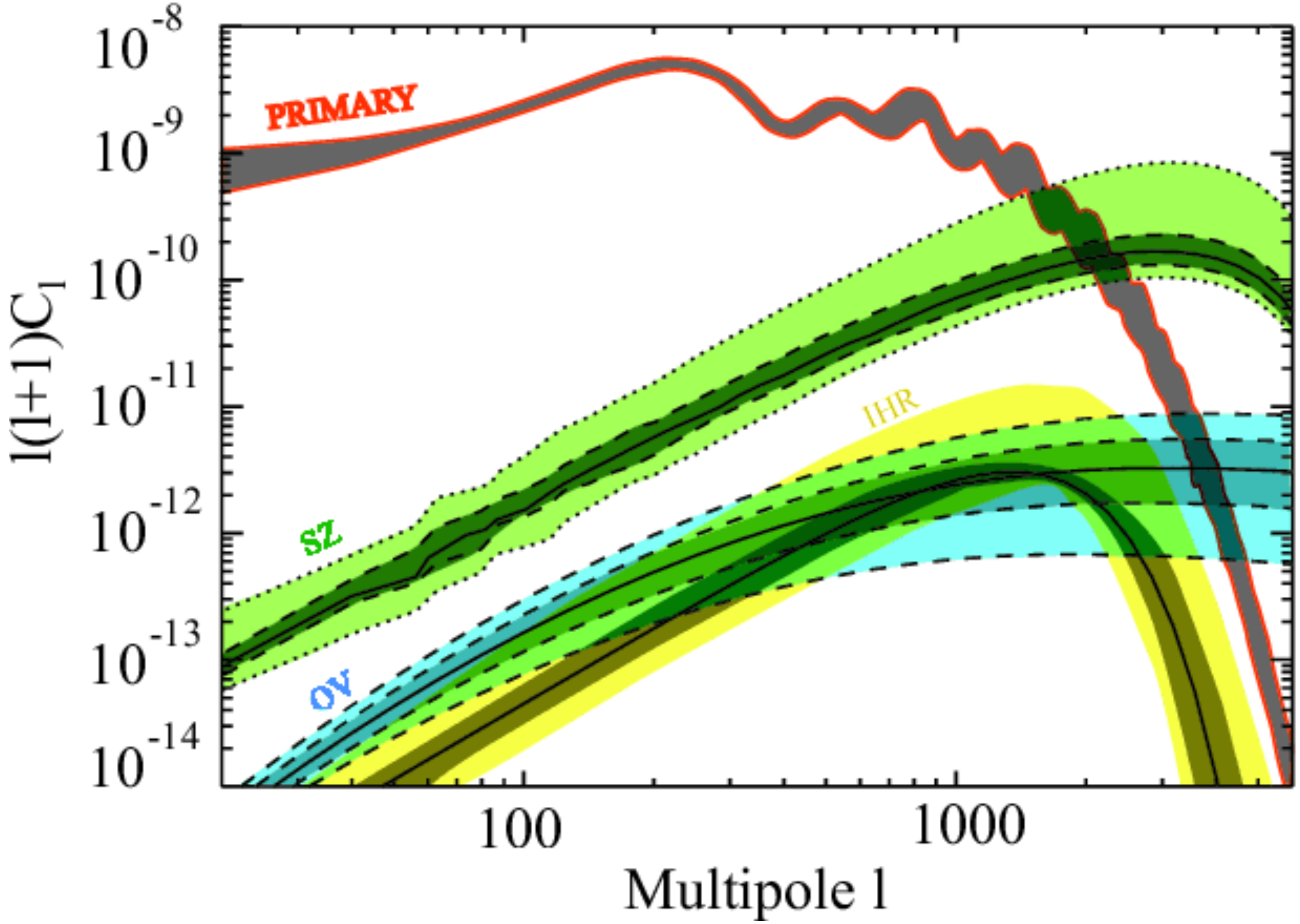
- relevance of secondary effects

for $l > 3000$ lensing and tSZ dominate anisotropies!



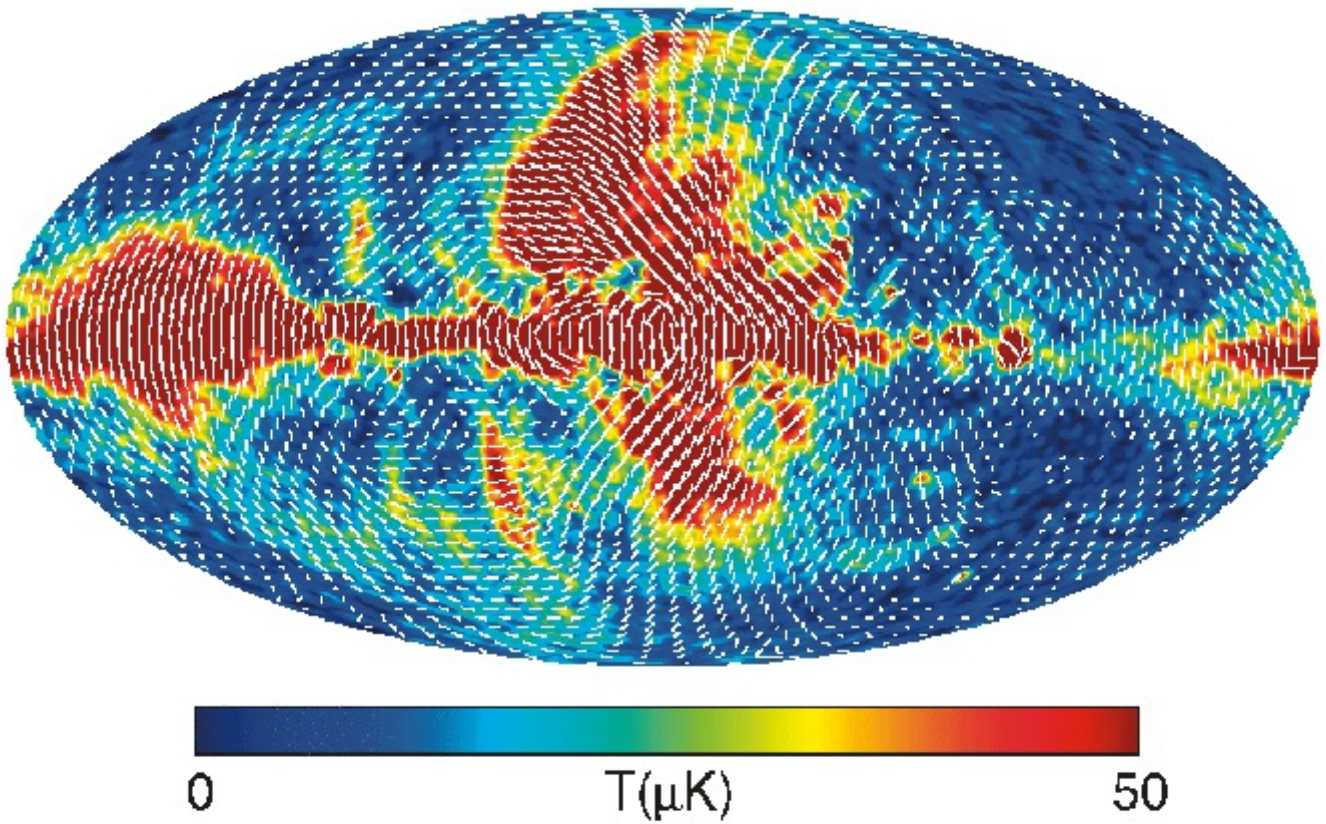
(Gnedin & Jaffe, 2000)

- relevance of secondary effects



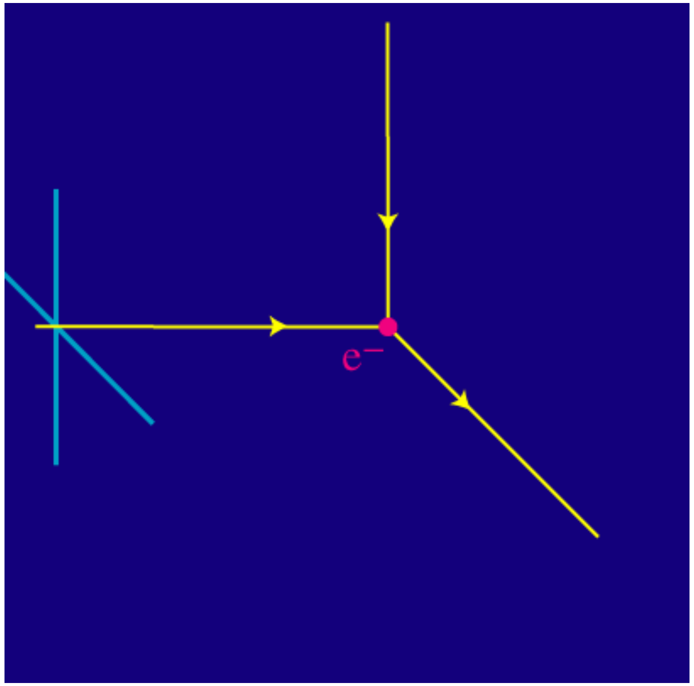
(Agjanim et al. 2002)

- discovery
- origin
- **CMB fluctuations**
  - primary (created during inflation)
  - secondary (created after photon decoupling)
  - **polarisation**

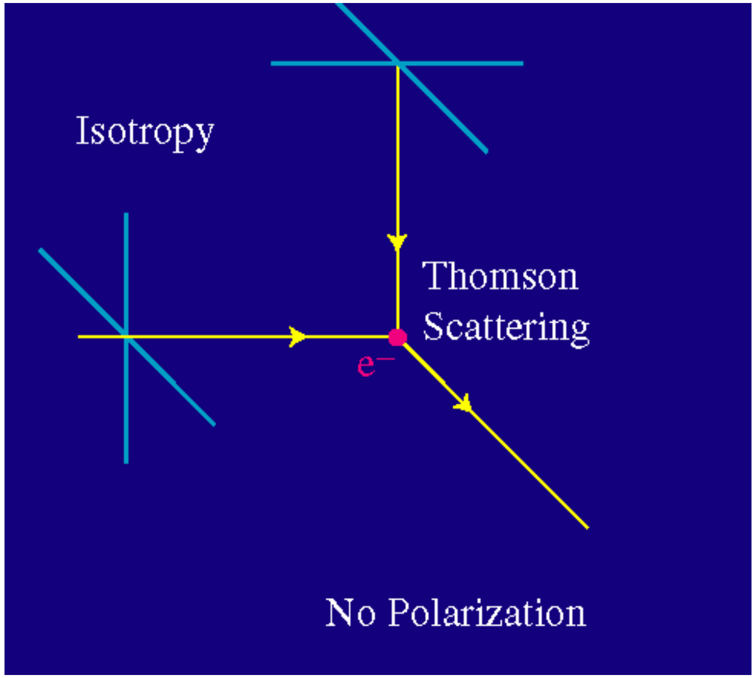


Hinshaw et al. 2008

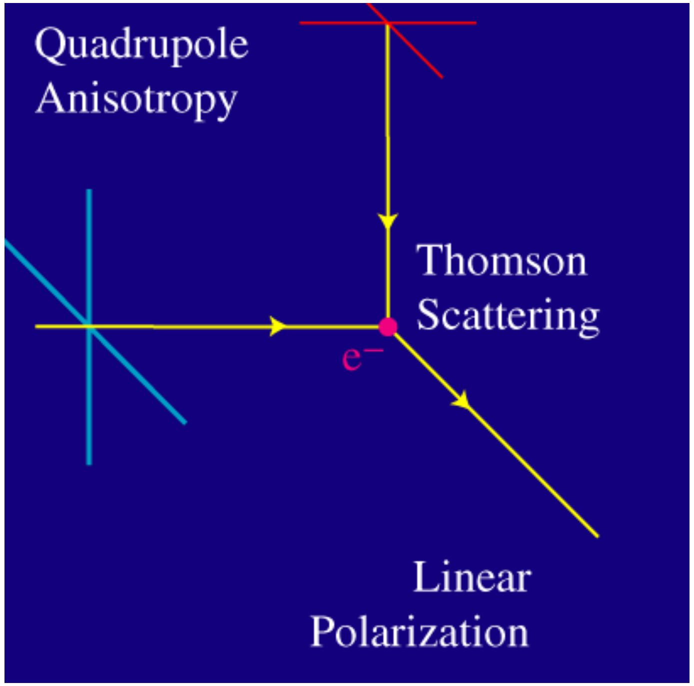
- Thomson scattering
  - the scattered wave is polarised perpendicular to the incidence direction
  - light cannot be polarised along direction of motion:
    → only one linear polarisation state gets scattered



- Thomson scattering
  - the scattered wave is polarised perpendicular to the incidence direction
  - incidence directions are isotropic → no net polarisation



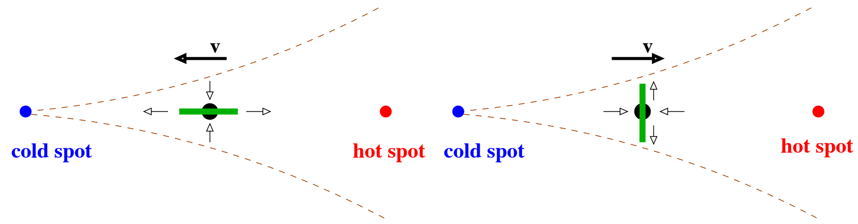
- Thomson scattering
  - the scattered wave is polarised perpendicular to the incidence direction
  - incidence directions has quadrupole → net polarisation



(these are only E modes)

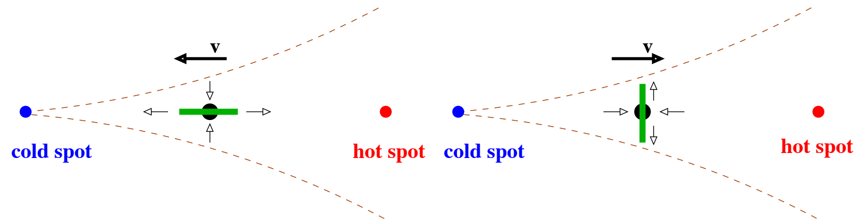
- CMB polarisation
  - quadrupole anisotropy in photon flux due to…
    - scalar perturbations (density)
    - vector perturbations (vorticity)
    - tensor perturbations (grav. waves)

- CMB polarisation
  - quadrupole anisotropy in photon flux due to…
    - scalar perturbations (density)
      - E-mode polarisation

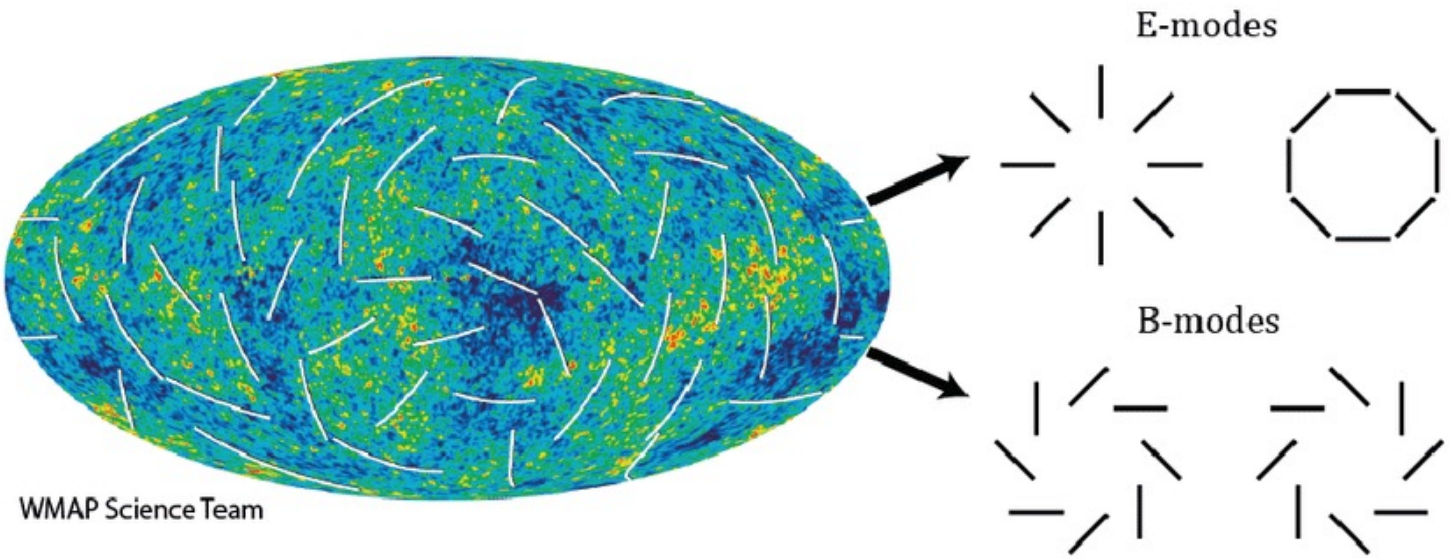


    - tensor perturbations (grav. waves)
      - B-mode polarisation

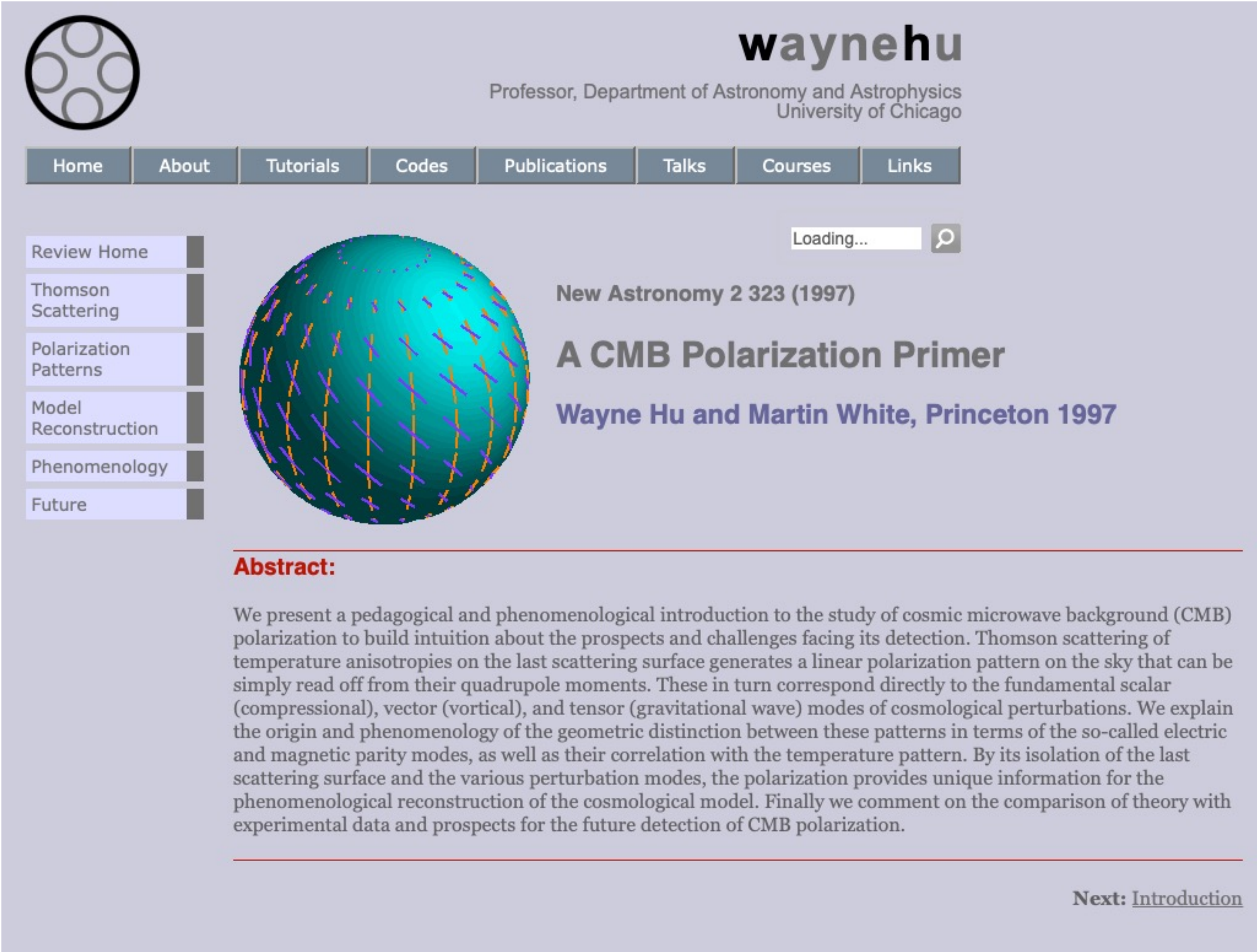
- CMB polarisation
  - quadrupole anisotropy in photon flux due to…
    - scalar perturbations (density)
      – E-mode polarisation



    - tensor perturbations (grav. waves)
      – B-mode polarisation



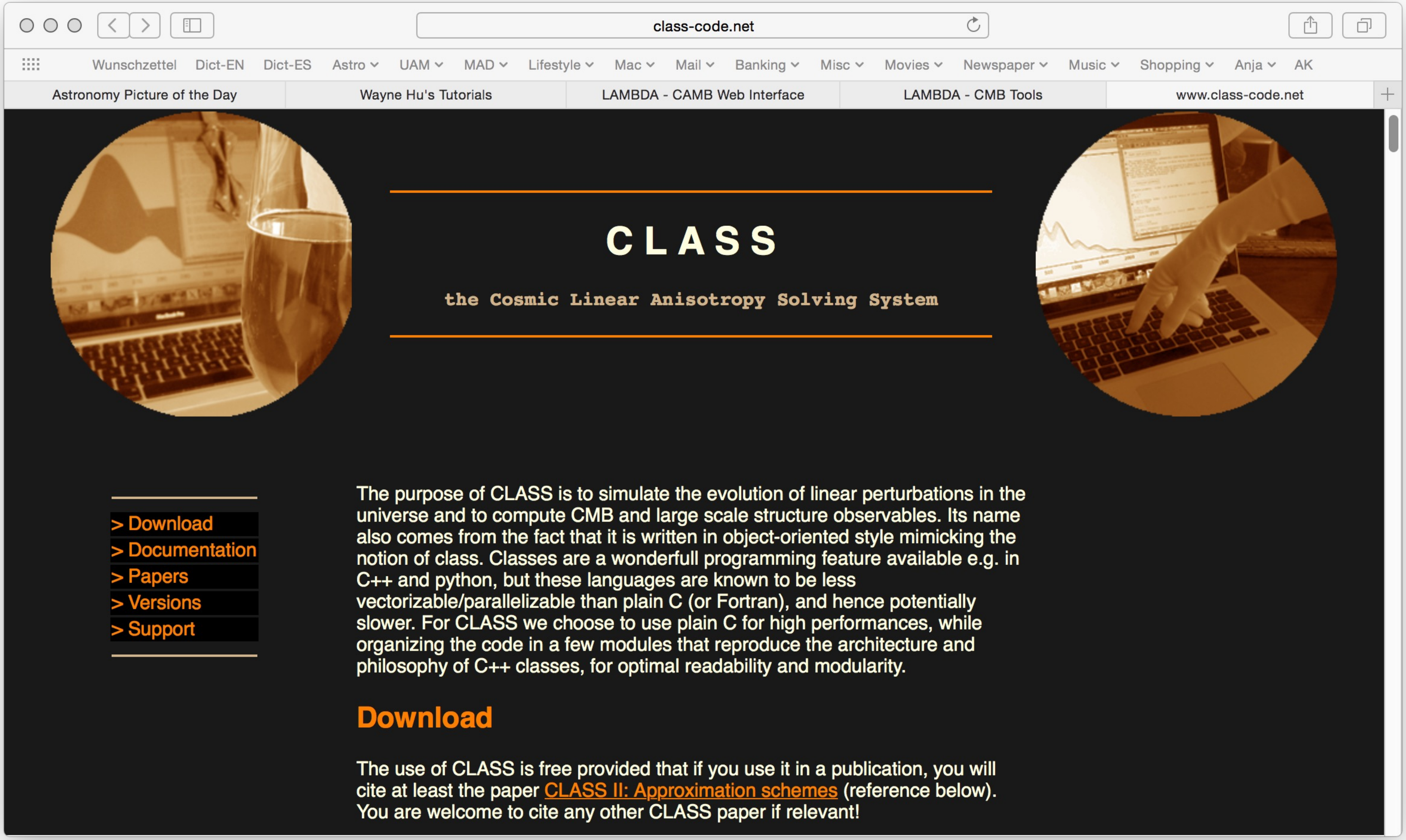
- CMB polarisation



http://background.uchicago.edu/~whu/polar/webversion/polar.html

Cosmic Microwave Background

http://www.class-code.net



Cosmic Microwave Background

http://lambda.gsfc.nasa.gov/toolbox/tb_camb_form.cfm